# Collaborative Agent-Based Information Processing for Intelligent Human Computer Interaction (iHCI) in Mixed Reality

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This thesis entitled:

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The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

Liu, Charles Zhenzhong (Ph.D. in Computing)

**Collaborative Agent-Based Information Processing for Intelligent Human Computer Interaction (iHCI) in Mixed Reality**

Thesis supervised by Associate Prof. Manolya Kavakli, Dr. Scott McCallum & Dr. Len Hamey.

The primary goal of this thesis is to explore collaborative agent-based information processing solutions for intelligent human-computer interaction (iHCI) systems in mixed reality applications. The thesis mainly focuses on the following research questions: 1) What are the major components of an iHCI framework for mixed reality? 2) How can we simulate human's visual processing in iHCI to differentiate the target of interest in mixed reality? 3) How can we design a knowledge-based information system to model human experience in mixed reality scene fusion? 4) How can we optimize the processes to improve the joint performance of human and computer in an iHCI system? 5) How can we manage dispersed, distributed but collaborative information processing in an iHCI system using an agent-based system architecture? 6) How can we guarantee the information security in an iHCI system for mixed reality?

In the thesis, we propose an agent-based iHCI system framework for collaborative information processing. We investigate the use of a number of methods, such as context-based pattern analysis, target-of-interest differentiation, user experience estimation, subspace learning, confidential data exchange, etc., as parts of a modular system. Each agent in the iHCI system is designed with specific

functionalities to support the system. We validate the system using a proof of concept for each module. The synthesis of the modules stand as a showcase to demonstrate the feasibility of the solution.

The main contributions of this research include: 1) a framework of an iHCI system; 2) an agent-based collaborative information processing architecture; 3) a modular system for mixed reality fusion and novel methods 4) for target of interest (TOI) differentiation using enhanced matting and recursive learning, 5) for dynamic layering with motion detection and adaptive learning, 6) for modeling context-based awareness and pattern analysis for TOI differentiation, 7) for quality of experience and quality of service using data-aware computing and evaluation of user-experience, 8) for user identification based knowledge database management, 9) for system security using communication and detection methods such as confidential tunnel and data-aware masquerading detection.

Our findings state that the proposed framework can provide an agent-based solution to design and implement an iHCI system. The thesis answers the six research questions by developing novel methods as stated in the main contributions above. These research results can also be used for improving the design and implementation of iHCI systems for mixed reality applications.

# Statement of Candidate

I certify that the work in this thesis entitled " Collaborative Agent-Based Information Processing for Intelligent Human Computer Interaction (iHCI) in Mixed Reality " has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree to any other university or institution other than Macquarie University.

I also certify that the thesis is an original piece of research and it has been written by me. Any help and assistance that I have received in my research work and the preparation of the thesis itself have been appropriately acknowledged.

In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature:

CHARLES ZHENZHONG LIU 15 March 2018

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# Publications

Throughout this thesis, we have produced 3 journal and 9 conference papers as well as 2 manuscripts. Twelve of these papers as demonstrated in Chapter 1, page 32, has been submitted for examination. The peer-reviewed publications produced in this thesis are listed below in a chronological order:

- C.Z. Liu, M. Kavakli, **Data-Aware Quality of Experience - Quality of Service Management**. Proceedings of IEEE Conference on Industrial Electronics and Applications (Hefei, China, Jun. 5-7, 2016), IEEE, pp. 1823-1828, 2016.(ERA A, EI Compendexed, Nominated for Best Paper Award).

- C.Z. Liu, M. Kavakli, **Fuzzy Knowledge Based Enhanced Matting**, Proceedings of IEEE Conference on Industrial Electronics and Applications (Hefei, China, Jun. 5-7, 2016), IEEE, pp. 934-936, IEEE, 2016.(ERA A, EI Compendexed).

- C.Z. Liu, M. Kavakli, **Extensions of Principal Component Analysis with Applications on Vision Based Computing** Multimedia Tools and Application, Springer Germany, vol. 75(17), pp. 10113-10151, 2016.(Impact Factor: 1.331, SCI Compendexed)

- C.Z. Liu, M. Kavakli, **Mixed Reality with a Collaborative Information System**, Proceedings of Asia-Pacific Services Computing Conference (Zhangjiajie, China, Nov 16 - 18, 2016), Springer, pp. 205-219, 2016.(ERA B, EI Compendexed, Nominated for Best Paper Award)

- C.Z. Liu, M. Kavakli, **Knowledge Based Pattern-Context-Aware Stereo Analysis and Its Applications**. Proceedings of The International Conference on Digital Image Computing: Techniques and Applications (Gold Coast, Australia, Nov. 30 - Dec. 2, 2016), IEEE, pp.164-171, 2016.(ERA B, EI Compendexed)

- C.Z. Liu, M. Kavakli, S. MacCallum and L. Hamey, **Motion-keying Based Dynamical Scene Layering with Adaptive Learning**. Proceedings of International Conference on Computer and Automation Engineering (Sydney, Australia, Feb. 17 - 21, 2017), ACM, pp.no. 111-115, 2017.(EI Compendexed; Best Paper Award).
- C.Z. Liu, M. Kavakli, **Scalable Learning for Dispersed Knowledge Systems**, Proceedings of Annual International Conference on Mobile and Ubiquitous Systems: Computing, Networking and Services (Hiroshima, Japan, Nov 28 Dec 1, 2016), ACM, pp. 125-134, 2016.(ERA A, EI Compendexed).
- Charles Z. Liu, Hasan Alyamani, Manolya Kavakli, **Behavior-Intention Analysis and Human-Aware Computing: Case Study and Discussion**, Proceedings of IEEE Conference on Industrial Electronics and Applications (Singapore, Jun. 18-20), pp. 1-6, 2017. (ERA A, EI Compendexed). In press.
- C.Z. Liu, M. Kavakli, **A Data-Aware Confidential Tunnel for Wireless Sensor Media Networks** Multimedia Tools and Application Springer Germany, pp. 1-23, 2017.(Impact Factor: 1.331, SCI Compendexed)
- C.Z. Liu, M. Kavakli, **An Intelligent HCI Framework Using Agent-Based Computing in Mixed Reality** The International Journal of Virtual Reality, vol. 17 (03), pp. 1-14, 2017.
- C.Z. Liu, M. Kavakli, **An Agent-Based Collaborative Information Processing System for Mixed Reality Applications Part A: Agent-Aware Computing**, Proceedings of IEEE Conference on Industrial Electronics and Applications (Wuhan, China, May 31 - Jun. 2), IEEE, pp. 1-6, IEEE, 2018. Accepted.(ERA A, EI Compendexed, Nominated for Best Paper Award).
- C.Z. Liu, M. Kavakli, **An Agent-Based Collaborative Information Processing System for Mixed Reality Applications Part B: Agent-Based Collaborative Information Processing and Coordination**, Proceedings of IEEE Conference on Industrial Electronics and Applications (Wuhan, China, May 31 - Jun. 2), IEEE, pp. 1-6, IEEE, 2018. Accepted.(ERA A, EI Compendexed, Nominated for Best Paper Award).
- C.Z. Liu,M. Kavakli, **Knowledge Based Adaptive Fuzzy Strategy for Target of Interest Differentiation with Its Application in Enhanced Matting**, manuscript submitted to Elsevier.
- C.Z. Liu,M. Kavakli, **An Agent-Based Collaborative Information System Based on Intelligent HCI Framework for Mixed Reality Applications**, manuscript submitted to Springer.

# Glossary

### Terminology Starting with A

- **agent**: independent computing entity or acting sections of code and data that represent active, interacting pieces of a model or system.
- **agent based modeling (ABM)**: a method of simulating the real world in which individual agents interact with their environment and each other to simulate real-world behaviors and conditions.
- **artificial intelligence (AI)**: the subfield of computer science that involves the creation of programs that attempt to do what was formerly believed to be able to be done by humans.
- **awareness**: an ability to know if something exists, or understand a situation or subject based on information or experience, and being aware of particular information, knowledge or experience, or people that exist.
- **awareness computing**: the use or operation of computers to simulate or give awareness to computer-based systems.
- **anonymous sample**: an uncertain data of sample that is not identified by its value, features or attributions.
- **anomalous data**: the data are deviating from what is standard, normal, or expected. It also refers to as outliers, novelties, noise, deviations, and exceptions.
- **anomaly detection**: outlier detection, the identification of items, events or observations which do not conform to an expected pattern or other items in a data-set.
- **adaptivity**: being in a state that has a capacity for adaptation.

- **adaptive learning**: a method or strategy for a computer-based system to have the ability to learn the circumstance without being explicitly programmed. It helps to adjust the parameters that vary or are initially uncertain to operation adaptively in response to the situation and performance feedback.
- **architecture**: the process and the product of planning, designing, and constructing structures. In computer science, it refers to fundamental structures of a computer system, the discipline of creating such structures, and the documentation of these structures. It contains elements of the system, relations among them, and properties of both elements and relations.
- **autonomous**: controlled by computer programs and not people.
- **abstraction**: removing detail of something to focus on a subset of the features without confusing details.
- **augmented reality**: an experience in a direct or indirect view of a physical, real-world environment, where some elements of which are augmented by computer-generated information.
- **argument**: one of the pieces of data provided as input to a procedure or function through the call to the procedure or function.
- **algorithm**: a set of instructions for accomplishing a task that when executed will terminate.
- **aggregation**: the formation of things into a cluster. In this thesis, it mainly refers to a theoretical model of a data-set with high-level conceptual abstraction.

**Terminology Starting with B**

- **behavior**: the way in which one acts or conducts oneself, especially towards others. In the computing context, it refers to the way in which a machine or natural phenomenon works or functions, such as what a system or a subject will do in response to its external environment without referring to details on implementation.
- **bandwidth** : the volume of information that can be transmitted or processed (e.g., bits/byte per second).
- **broadcast**: to send the same message to all who can listen in messaging passing.
- **binary**: the base 2 number system that integer can be encoded as a binary which is a string of 0 and 1.

- **buffer**: a location, especially in RAM, for storage of temporary data to speed up an operation such as disk access or printing.
- **BIOS**: Basic Input/Output System that gives the computer a platform to run the software using a floppy disk or a hard disk.
- **bit**: a digit number, either a 0 or a 1. The binary digit is used to represent computerized data.

**Terminology Starting with C**

- **computer science** : the study of process, data and computation.
- **computational intelligence (CI)**: the ability of a computer to learn a specific task from data or experimental observation.
- **computing**: the use or operation of computers, processing with computation.
- **computing structure**: a systematic structure that defines how computing operations are directed toward the achievement of aims.
- **computing entity**: an element contributes to functional operations and processing in a computing structure or a computer-based system. Its information can be stored and processed as well.
- **collaborative information processing**: a strategy or a method to process information by coordinating many distributed computing entities work together in an organizational structure.
- **collective**: a group of entities that share or are motivated by at least one common issue or interest, or work together to achieve a common objective.
- **collective behavior**: in this thesis, it mainly refers to a type of process and result caused by the behavior of a group of entities collaborating under coordination in organizational structure.
- **class**: a group of objects having same operations and attributes is defined as a class.
- **cloud**: information being stored on a distant mass storage device accessible via a computer network.
- **cloud computing**: the computation is on distant machines accessible via a computer network.
- **cloud storage**: the information is stored on distant machines accessible via a computer network.

- **context**: the circumstances or conditions that form the setting for an event, statement, or idea, and regarding which it can be understood.
- **context-based computing**: a type of processing that enables systems to process the set of circumstances or facts during the interaction and processing.
- **context of interaction**: the context of the scenario related to the perception in a real world that surrounds the subject in a particular event, situation, etc.
- **context of the system environment**: the context of the cyber-environment related to the devices, operations, and processes to perform the functionalities in the system.
- **CMOS**: an abbreviation for Complementary Metal-Oxide-Semiconductor, the battery-powered chip that is situated on the Motherboard that retains system information such as date and time.

**Terminology Starting with D**

- **data** : the information that is saved on a computer.
- **data-aware**: refers to a system or computation that optimizes itself and its processing based on the data.
- **data mining**: using algorithms to infer complex results for masses of data.
- **database**: an organized collection of data and services to access them in a variety of ways relevant to the data.
- **device**: a unit or piece of hardware with a specific purpose in a system such as a data gloves, disk, keyboard, audio board, etc.
- **drone**: an unmanned flying vehicle.

**Terminology Starting with E**

- **entity** : a thing with distinct and independent existence. It mainly refers to computing entity in this research.
- **enhanced mixed reality (eMR)** : a mixed reality system with intensified qualities and functionalities. In this thesis, it refers to the mixed reality system with enhanced user-experience adapted performance, information processing, data management and information security.

**Terminology Starting with F**

- **framework** : a basic supporting part or structure. In computer science, it means an abstraction in which computer system is providing generic functionality for application-specific processing. It provides a standard way to build and deploy applications.

- **function**: a type of procedure or routine. Some programming languages make a distinction between a function, which returns a value, and a procedure, which performs some operation but does not return a value.

**Terminology Starting with G**

- **global positioning system (GPS)**: a global navigation satellite system that provides geolocation and time information to a GPS receiver anywhere on or near the Earth where there is an unobstructed line of sight to four or more GPS satellites.

- **geographic information system (GIS)**: a system designed to capture, store, manipulate, analyze, manage, and present spatial or geographic data. It is an application of location-based analytics ?using the science of geographical intelligence to analyze multiple, complex datasets layered over defined territories, revealing hidden trends and patterns.

**Terminology Starting with H**

- **HASH**: a function or a type of processing to map data of arbitrary size to data of fixed size, and the values returned are called hash values, hash codes, digests, data fingerprint, or simply hashes.

- **human-aware computing**: an autonomous computing for a system to perceive, feel, and be conscious of events, objects, or sensory patterns for human-centric inter-operation.

- **human-system performance**: human-system joint performance, a comprehensive evaluation of both sides of performance given human and system.

- **human-system performance sensing**: a computing a method to enable the system to perceive and process the human-system performance.

**Terminology Starting with I**

- **intelligent computing** : a type of computing enable a computer to perform computational intelligence.

- **immersion** : deep mental involvement in something.

- **image domain**: the domain in which the arrangement and relationship among different gray level intensities (pixels) are expressed.

- **immersive interaction**: in this thesis, it refers to a computer-based interaction that makes a user feel immersion while interacting with the environment in a natural, intuitive manner.
- **interactive systems**: computer-based systems with significant amounts of interaction between humans and the computer. In this thesis, it mainly refers to HCI systems.
- **information science**: a field primarily concerned with the analysis, collection, classification, manipulation, storage, retrieval, movement, dissemination, and protection of information.
- **information processing**: processing of information in any manner detectable by an observer to convert latent information into manifest information. In this computer science, it mainly refers to data processing that removes the uncertainty and trivial details in the received data and manifests the information of interest.

**Terminology Starting with J**

- **jump search**: block search, a search algorithm for ordered lists.

**Terminology Starting with K**

- **kernel**: a weighting function used in kernel density estimation to estimate the probability density function of a random variable. It can be used as a transition function of a stochastic process.

**Terminology Starting with L**

- **learning**: a process of acquiring new or modifying existing knowledge, behaviors, skills, values, or preferences. In this thesis, it mainly refers to machine learning.

**Terminology Starting with M**

- **mixed reality**: hybrid reality, the merging of real and virtual worlds to produce new environments and visualizations, encompassing both augmented reality and augmented virtuality with reproduced multimedia metaphors (related to senses of sight, hearing, and even smell, taste and touch).
- **machine learning**: a field of computer science that gives computers the ability to learn without being explicitly programmed.

**Terminology Starting with N**

- **network**: a computer network, a data network or a digital telecommunications network which allows nodes to share resources.

- **network computing**: a type of computing that networked computing devices exchange data with each other using a data link.

- **network energy efficiency (NEE)**: a metric to measure the efficiency of the energy consumed during the communication in a network, defined as a ratio of the energy used for data communication to the energy consumed totally in the network.

- **network energy efficiency under packet error rate (NEE-PER)**: the network energy efficiency under a given packet error rate.

- **network energy efficiency under packet loss rate (NEE-PLR)**: the network energy efficiency under a given packet error rate.

- **NOR**: joint denial, a logic operation or a truth-functional operator which produces a result that is the negation of logical or. It gives a positive output only when both inputs are negative.

**Terminology Starting with O**

- **Open (systems)**: a type of system environment with external interactions, providing some combination of interoperability, portability, and open software standards. In this thesis, it refers to computer-based systems that allow unrestricted access by people and/or other computers.

**Terminology Starting with P**

- **parallel computing**: a type of computation in which many calculations or the execution of processes are carried out simultaneously. Large problems can often be divided into smaller ones, which can then be solved at the same time.

- **pervasive computing**: a type of computing is made to appear anytime and everywhere using any device, in any location, and in any format.

- **peer-to-peer (P2P)**: a computing or networking application with a distributed architecture that partitions tasks or workloads between peers. The peers are equally privileged, equipotent participants in the application, which can be modeled as P2P nodes.

- **public key cryptography (PKC)**: an encryption technique that uses a paired public and private key (or asymmetric key) algorithm for secure data communication. A message sender uses a recipient's public key to encrypt a message. To decrypt the sender's message, only the recipient's private key may be used.

- **public key cryptosystems (PKCs)**: a type of cryptographic system that uses pairs of keys: public keys which may be disseminated widely, and private keys which are known only to the owner.

### Terminology Starting with Q

- **quality of service (QoS)**: the description or measurement of the overall performance of a service, such as telephony or a computer network or a cloud computing service, particularly the performance seen by the users of the network.

- **quality of experience (QoE or QoX)**: a measure of the overall level of customer satisfaction.

### Terminology Starting with R

- **remote**: Equipment or site that is located out of the way or at a distance from primary equipment or a larger or primary site. Sometimes used as the opposite of local.

- **remote access**: the ability to access a computer from outside a building in which it is housed. Remote access requires communications hardware, software, and actual physical links, although this can be as simple as common carrier (telephone) lines or as complex as TELNET login to another computer across the Internet.

- **recursive learning**: a learning strategy characterized by recurrence or repetition of a rule, definition, or procedure to successive results. In programming, it mainly refers to a method for solving a particular problem by breaking the task into smaller subtasks and designing as a self-containing procedure to run for machine learning.

### Terminology Starting with S

- **smart systems**: systems that incorporate functions of sensing, actuation, and control to describe and analyze a situation and make decisions based on the available data in a predictive or adaptive manner, thereby performing smart actions.

- **system performance sensing**: a computing to enable the system aware of its devices, network, and operations related to the performance and processing.

### Terminology Starting with T

- **trimap**: a pre-segmented image consisting of three regions of foreground (what you want to cut out), background and unknown. Partial opacity values are then computed only for pixels inside the unknown region.

### Terminology Starting with U

- **uniform space distribution** : also known as uniform spatial distribution that the probability of the samples in Euclidean spatial domain subject to uniform distribution.

- **uniform frequency distribution** : the probability distribution that the probability of the samples in frequency domain subject to uniform distribution.

- **ubiquitous computing** : pervasive computing.

- **ubiquitous networking**: pervasive networking, a distribution of communications infrastructure and wireless technologies throughout the environment to enable continuous connectivity. That capacity is an essential component of pervasive computing.

- **user experience (UX)**: a person's emotions and attitudes about using a particular product, system or service. It includes the practical, experiential, affective, meaningful and valuable aspects of humancomputer interaction and product ownership.

**Terminology Starting with V**

- **virtual reality**: an alternate world filled with environments nearby by electronic simulations and computer-generated images to enable the end user to interact with the virtual space realistically.

- **visual computing**: a generic term for all computer science disciplines handling with images and 3D models, i.e., computer graphics, image processing, visualization, computer vision, virtual and augmented reality, video processing.

**Terminology Starting with W**

- **wearable computing**: miniature electronic devices that are worn under, with or on top of clothing.

**Terminology Starting with X**

- **exclusive OR (XOR)**: a binary logic operation that gives a true output when the number of true inputs is odd. An XOR computation implements an exclusive or; that is, a true output result if one, and only one, of the inputs to the system, is true.

**Terminology Starting with Z**

- **zero-crossing**: a point where the sign of a mathematical function changes (e.g., from positive to negative), represented by a crossing of the axis (zero value) in the graph of the function. It is a commonly used term in electronics, mathematics, sound, and image processing.

**Terminology Starting with Number**

- **2D (computer graphics)** : a computer-based generation of digital images based on two-dimensional models. The word may stand for the branch of computer science that comprises such techniques, or for the models themselves. 2D computer graphics are mainly used in applications that were originally developed upon traditional printing and drawing technologies, such as typography, cartography, technical drawing, advertising, etc.

- **3D (computer graphics)**: graphic arts that were created with the aid of digital computers and specialized 3D software. In general, the term may also refer to the process of creating such graphics, or the field of study of 3D computer graphic techniques and its related technology. 3D computer graphics are different from 2D computer graphics in which a three-dimensional representation of geometric data is stored in the computer for the purposes of performing calculations and rendering 2D images. Sometimes these images are later displayed in a pre-rendered form, and sometimes they are rendered in real-time.

- **3D modeling**: three-dimensional modeling, refers to the process of developing a mathematical representation of any surface of an object (either inanimate or living) in three dimensions.

# Contents

# Tables

**Table**

# Figures

**Figure**

# Chapter 1

# Introduction

## 1.1 Towards Intelligent HCI (iHCI)

In the paper titled “A Brief History of Human Computer Interaction Technology” [423], Myers stated that “As computers get faster, more of the processing power is being devoted to the user interface. The interfaces of the future will use gesture recognition, speech recognition and generation, ‘intelligent agents,’ adaptive interfaces, video, and many other technologies now being investigated by research groups at universities and corporate labs (Reddy, 1996) [494]. It is imperative that this research continue and be well-supported.” Considering that we are now in future, two decades further than this statement, it is time to investigate the role of intelligent agents in HCI. In this thesis, we are primarily interested in intelligent human-computer interaction (iHCI) as opposed to simple human computer interaction (HCI), as defined by Lew et al. [330], by giving the following sample:

“When a user types a document at a word processor, there is a form of simple human-computer interaction - the human types and the computer shows the human the formatted keystrokes composing the document. However, this would not be considered intelligent interaction because the computer is not performing any intelligent processing on the keystrokes; there is no meaning extracted from the user’s actions. The computer is simply mirroring the user’s actions.”

From a research perspective, we refer to intelligent interaction where the computer understands not only the meaning of the user’s message as well as its context. As an example, again given by Lew et al. [330], “interaction between humans is typically performed using speech and body gestures. The speech carries the meaning of the message but often not the context. To understand the context, it is also necessary to grasp the facial and body gestures. If we are to have truly intuitive communication, computers will need to have their own sense of vision and speech to naturally fit into the world of humans.”

Collazos argued that for truly achieving effective Intelligent Human-Computer Interaction, there is a need for the computer to be able to interact naturally with the user, similar to the way human-human interaction takes place [121].

The term ”Human-Centered Computing” is used to emphasize the fact that although all existing information systems were designed with human users in mind, many of them are far from being user friendly [330]. Among the several fundamental directions for the future in HCI research,Lew et al [330] state two requirements, which this thesis focus on:

- understanding -which involves learning more about the user and creating systems which will adapt appropriately to the user's needs;
- education and knowledge -which involve developing new paradigms which improve education, learning, and the search for knowledge.

Intelligent User Interfaces are in the intersection of AI, psychology, HCI and often related fields as seen in Figure 1.1. As stated by Ehlert [464], "Intelligent user interfaces (IUIs) try to solve human-computer interaction problems by providing new methods of communication and by adapting to the user." Some of these communication methods focus on natural language systems, gesture recognition, image recognition, and multi-modal interfaces. "Adapting to the user is executed by using artificial intelligence (AI) techniques to perform reasoning and learning. Intelligent interface agents, which are anthropomorphic computerized beings, combine several of these techniques and try to help the user by automating a particular task" [464]. This thesis is limited with the investigation of the use of AI and intelligent HCI agents, as well as image recognition techniques as a primary concern of Mixed Reality systems in terms of visualization.

"Intelligent user interfaces (iUIs) specifically aim to enhance the flexibility, usability, and power of human-computer interaction for all users. In doing so, they exploit knowledge of users, tasks, tools, and content, as well as devices for supporting interaction within differing contexts of use" [394]. Adaptation and problem solving are important topics addressed by research on artificial intelligence (AI) and therefore many IUIs draw heavily on the techniques developed in AI research [464].

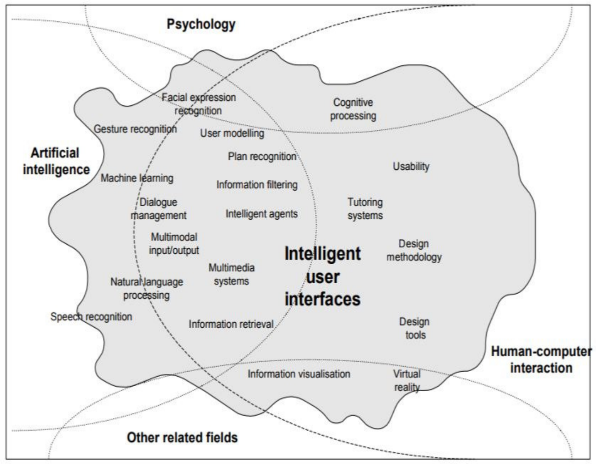


Figure 1.1: iHCI and related fields [464]

In the 1960s there was a technology-driven focus on HCI (e.g., [99, 242]). In the 1970s the user started to become the focus of attention [150, 245, 487].In the 1980s HCI had turned into a user-centered research field with usability as its main goal and technology as a supporting tool [436–438]. The WIMP (Windows, Icons, Menus, Pointers) model became widespread and became a guiding principle for all interfaces [75, 152]. Although during the late 1980s and 1990s these were enhanced with embedded context-menus, new types of input devices such as mice, joysticks and other controls, the basic technology has not changed much [58, 552].

One of the major problems in HCI as stated by Ehlert [464] is that new technologies such as data mining, machine learning, speech recognition, and computer vision are difficult to use with the existing interfaces. In 1994, intelligent agents and recommender systems started to appear on Internet [118]. In 1996, speech and natural language recognition applications appeared [513]. In 1997, Microsoft released their "intelligent" Office assistant help system [613, 637]. However, since then progress on iHCI for the commercial market seems to have come to a stop and only a few iHCI have appeared in recent years [380, 428, 492]. There is clearly a gap in literature regarding the frameworks for iHCI systems. Therefore, in this thesis our goal is to investigate potential solutions to this problem, particularly using collaborative agent-based systems and context awareness as we will discuss in the next section.

## 1.2 Background

The goal of this thesis is not to review VR, AR and MR literature in detail but to provide an overview of the technology to be able to define a starting point to undertake research and contribute to the development of an iHCI framework in the field. The earlier surveys of [31, 32, 64, 90, 602, 679] provide a good review of the current state of the art in Augmented Reality. [218, 529, 655, 676] review the development of virtual reality with its applications in surgery, health care, and operation training. Mixed reality is a new scope. Its research and development start in recent years. Even though the related work is rare, some references [314, 351, 461, 605] can also provide an introduction to this novel development trend.

### 1.2.1 Virtual Reality

In computer science, Virtual Reality (VR) refers to an artificial environment that is created with software and presented to the user in such a way that the user suspends belief and accepts it as a real environment [119,205,564]. Generally, it is primarily experienced through senses by computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensors. A VR system may include a range of equipment for electronic simulations, such as head mounted displays [585], motion-capture suits [204], fiber-optic data gloves [246], stereoscopic goggles [273, 629], and stereo emitters [80].

George Coates defined it as "electronic simulations of environments experienced via head-mounted eye goggles and wired clothing enable the end user to interact in realistic three-dimensional situations" [119]. Jaron Lanier defined VR as a system applied to digital devices for applications such as training simulator for Information Age warfare [320]. Paul Greenbaum defined VR as "an alternate world, filled with computer-generated images that respond to human movements. These simulated environments are usually visited with the aid of an expensive data suit which features stereophonic video goggles and fiber-optic data gloves" [205]. Petri Parvinen et al. defined VR as "computer technologies that use software to generate the realistic images, sounds, and other sensations that represent an immersive environment and simulate a user's physical presence in this environment" [461]. From those definitions, we can see vision is an integral part of VR.

Applications of VR can be found in military uses [81, 504], space investigation [49, 81], flight and driving simulations [17, 225], medical training [188], and engineering design [634], to help researchers and engineers to conduct experiments with more flexible and low-cost solutions than traditional techniques in safer conditions than experience in reality.

One of the important characteristics of VR is interaction [69, 482], and the other is immersion. VR can be divided into three kinds [81]:

- textual VR, which refers to interaction without visualization (see e.g., Figure 1.2);
- desktop VR, interaction with desktop immersion (see e.g., Figure 1.3);
- and immersive VR, interaction with high immersion (see e.g., Figure 1.4).

**Remark 1.** *Immersion refers to the perception of being physically present in a non-physical world; immersive interaction focuses more on user experience during an interaction. Interaction is still available even though when there is no immersion (e.g., in textual VR).*

### 1.2.2 Augmented Reality

Augmented Reality (AR) refers to an experience in a direct or indirect view of a physical, real-world environment, where some elements of which are


Figure 1.2: Textual VR Example: Text-based VR Game

augmented by computer-generated information. Sensory inputs, such as acoustics, vision, and positioning data, form the elements as augmented information for user [32]. Figure 1.5 gives an example of augmented reality application, where the user actually interacts with the real world with the support of the augmented digital information generated by a computer.

Ronald T. Azuma defined AR as “a variation of virtual environments (VE), or virtual reality as it is more commonly called” [31, 32]. From this perspective, AR may have some overlaps with VR, but the main purpose of AR is to provide supplementary information to support a certain task. Users in AR still interact with real world other than the virtual world.

Classically, AR superimposes computer-generated information on a user’s view of the real world across multiple sensory modalities, such as visual and auditory [443]. Thus, AR systems use similar equipment to VR, such as head mounted displays (HMD [398]), data-gloves [580], and sensor jackets [169], which

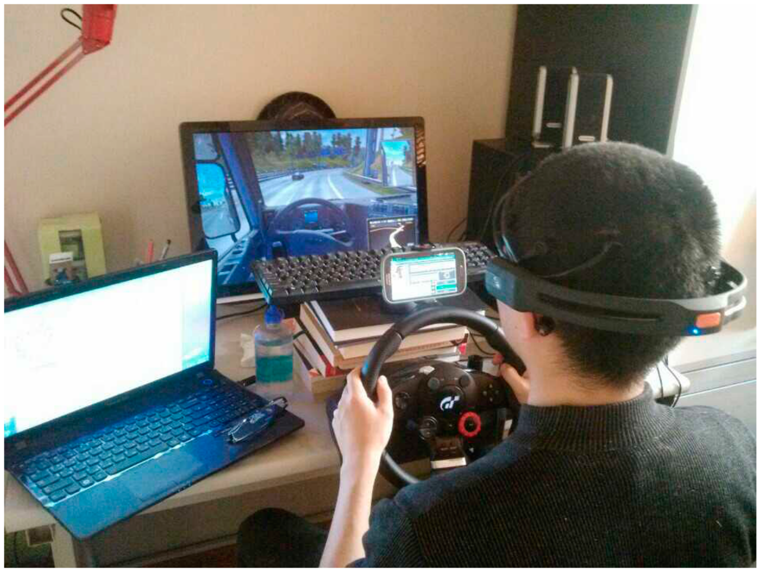

Figure 1.3: Desktop VR Example: Virtual Desktop

have been used in VR systems for acquiring sensory inputs. Compared to VR, which replaces the real world with simulated reality, the content of AR consists primarily of the real physical world through see-through displays with a little virtuality to 'augment' user's perception of reality.

Augmented virtuality serves as supplemented auxiliary for perceiving the world as the main part of the content. Therefore, many augmented reality systems are widely used in low-cost applications of immersive VR systems [283, 324, 443]. However, when stronger user experience is demanded during an immersive interaction, more virtuality is needed to reinforce the simulated interaction with augmented reality. This demand could be achieved by using a mixed form of virtual and real-world elements, with both kinds of elements augmented in the environment.

Figure 1.4: Immersive VR Example: Flight Simulation

### 1.2.3 Mixed Reality

Mixed reality (MR) [124, 405, 577] was proposed to perform merging of real with virtual (e.g., Figure 1.6, 1.7). MR refers to VR and AR scenarios to produce a cyber world with a mixture of reality and virtual reality. Due to the physical and digital coexistence, a mixed reality system allows individuals to experience a better immersive experience with reproduced multimedia metaphors (related to senses of sight, hearing, smell, taste, and touch), encompassing both augmented reality and augmented virtuality (i.e., the fusion of real-world elements into virtual worlds [405]).

Paul Milgram et al. defined mixed reality as "one in which real world and virtual world objects are presented together within a single display, that is, anywhere between the extrema of the virtuality continuum" [404, 405]. They introduced a concept of Virtual Continuum (VC) to represent the mixture of classes


Figure 1.5: Augmented Reality Example: Service Maintenance Application

of objects presented in any particular display situation (as shown in Figure 1.8). Petri Parvinen et al. defined mixed reality as "combining real and virtual contents with the aid of digital devices", which "consist of both augmented reality (i.e., virtual 3D objects in immersive reality), and augmented virtuality (i.e., captured features of reality in immersive virtual 3D environments)" [461]. From this perspective, mixed reality may consist of VR, AR, and physical reality, but represent a mixture of these three.

The concept of mixed reality also relates to research about immersive interaction for a realistic experience (e.g., [543, 556]). MR based immersive interactive systems have been widely applied to entertainment [140, 502], education [282, 401, 406], manufacturing [443], military [531] and health-care [321, 384]. MR systems enable users to interact with computer systems in immersive virtual-environments [32, 406, 441], providing possible improvement for high-level interaction, such as memory functioning [460], attention enhancement [111] and cognitive

Figure 1.6: Mixed Reality Example: Military Tactic Training

behavior therapy [297].

VR, AR, and MR sometimes may have some overlaps between each other, because they may use some similar techniques (e.g., 3D-modeling, computer graphic processing) and equipment (e.g., HMD, camera systems) to build their systems. We summarize their difference in features and environment (as shown in Table 1.1 and Table 1.2) to help distinguish.

### 1.2.4 Research Problem

To perform high-level interaction, modern computer systems have provided many auxiliary functionalities for data analysis and visualization [61,399]. Usually, in MR, sensors, and actuators are required (as in [71,215]). However, those devices play roles similar to keyboards and mice. This makes the interaction passive because the system does not actively collaborate with users. Users have to adapt their behavior to equipment operations. This may reduce the quality of user

Table 1.1: Features Comparison among VR, AR and MR

| Comparison | Features |
|---|---|
| Virtual Reality (VR) | totally computer generated world to allows user to interact with a totally virtual world |
| Augmented Reality (VR) | providing a way that user can get an indirect view of a real life scenario or environment with supplemented digital information |
| Mixed Reality (MR) | mixture of digital world and real world with combination of AR and VR |

Table 1.2: Environment Comparison among VR, AR and MR

| Comparison | Environment |
|---|---|
| Virtual Reality (VR) | totally virtual world built by digital elements surrounding and interacting with users |
| Augmented Reality (VR) | digital and other augmented elements superimposed in real life (they are not actually part of it) |
| Mixed Reality (MR) | a mixture of virtual and physical world with digital scenarios embedded in the real world surroundings |

Figure 1.7: Mixed Reality Example: Castle Game

experience and the usability of the system, particularly when users need assistance to complete tasks [563].

The concept of human-friendly iHCI is also important for high-level interaction. iHCI improves user experience and lifelike immersion [168, 272, 563]. It may reduce cognition load.

In iHCI design, when an application must perform autonomous interaction, the system has to process the context, especially for the users, the surroundings, and the relationships between them. In this case, how to enable the system to understand objects with a particular interest becomes an issue for the development of an iHCI system. Since satisfactory interaction between human and computer depends on the extent of the recognition, the system must be able to understand more about the users [72, 296]. This functionality is particularly desirable for the applications related to cyberpsychology.

For high-level interaction, MR systems must have greater ability to perform intelligent processing. This requires a **collaborative agent-based information**

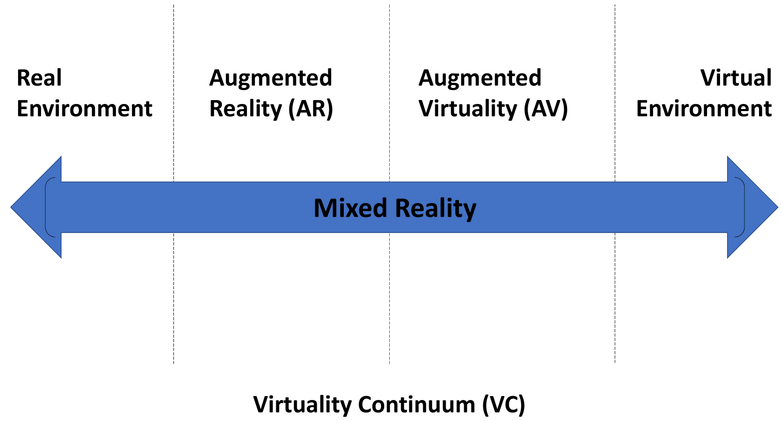


Figure 1.8: Simplified representation of a "virtuality continuum" [405]

**system (CABS)** that consists of human user and other computing entities as agents. The system must interact with human users as well as the agents.

The issues above motivate us to develop an iHCI framework for mixed reality. The goal and research questions in this thesis are explained in the next section.

## 1.3 Goal

This thesis focuses on how to apply intelligent computing to enhance the functionality of mixed reality systems and to improve user-experience, system performances and information security. We aim to develop an iHCI framework including, a collaborative agent-based information processing model that enables the systems to recognize the subjects and context in HCI. A Collaborative Agent-Based System (CABS) refers to multiple agents operating in the system, including human, devices and a combination of the humans and devices. CABS can analyze the features and attributes of multiple agents. The targets and subjects of the agents as well as their interaction and the results of this analysis must be modeled and stored as knowledge to complete a certain task.

Robert Reix et al. defined an information system as "an organized set of resources (hardware, software, people, data, processes) able to acquire, treat, store and export information (as data, text, pictures, sounds, etc.) in the organizations" [496]. Chantal Morley regarded that an information system consists of two components: "the information management system (including actors, data, and processes)", and "the computing system (including hardware and software resources, data base and functions)" [417]. From those definitions, it can be seen that the human (people) is an important factor. Some elements in an information system, such as data and processes, are also components of an agent-based system [174]. A Collaborative Information System (CIS) is an information system with collaborative elements and processes [55]. One of the features of an information system is collaboration [584]. Jihed Touzi suggested collaboration as "the flow of messages taking place between two parties for a given purpose" [103]. From this perspective, exchanging data flow is the common element between an agent-based system and an information system [174]. Therefore, we combine the agent-based system with a collaborative information system to make a collaborative agent-based information system [351].

The primary goal of this thesis is:

⋆ to explore solutions to enable HCI system to perform smart interaction using collaborative agent based information processing.

Expected outcomes are:

- to provide support for the implementations of vision-based iHCI systems for mixed reality applications;

- to propose a framework for an iHCI for mixed reality and collaborative agent based information processing.

## 1.4 Methodology and Technology

The iHCI system using MR is named as eMR (enhanced Mixed Reality) system [351]. Although an MR system can be enhanced in many aspects, this thesis mainly focuses on the specific enhancements described below. The methodology, technology, and the research question will be presented in the following section.

**Remark 2.** *eMR stands for enhanced Mixed Reality. It is an application of iHCI. With the use of iHCI in a mixed reality to enhance system's functionality, the system becomes an eMR system.*

### 1.4.1 Enhancements Required

To achieve the goal of investigating potential solutions for an iHCI model using collaborative agent-based information processing, we classify the enhancements required for collaborative agent-based information processing into three main groups (Figure 1.9):

(1) Visual Computing (VC) : Visual computing is a generic term for all computer science disciplines handling images and 3D models, i.e. computer graphics, image processing, visualization, computer vision, virtual and augmented reality, and video processing. Visual computing includes aspects of pattern recognition, human computer interaction, machine learning and digital libraries. The core challenges in visual computing are the acquisition, processing, analysis and rendering of visual information (mainly images and video) [210, 475], which are the main interests of this thesis;

(2) Sensing System Performance (SSP): This is required mainly to enable the system aware of its devices, network, and operations related to the performance and processing(e.g., [19, 407]). We mainly focus on quality of service (QoS), bandwidth consumption and information security in this thesis;

(3) Sensing Human-System Performance (SHSP): This is required mainly to enable the system to process both human related and system related issue (e.g., [40, 550]). We mainly focus on the system performance influence on quality of experience (QoE) in this thesis.

In Figure 1.9, VC mainly focuses on image fusion and simulating the attention to the target. SHSP focuses on user experience evaluation and joint performance evaluation. SSP focuses on devices authentication and system structure and operations. With the support of target of interest differentiation and evaluation of user-experience, the context of interaction can be modeled and processed as a type of computing awareness in the iHCI system to perform the tasks including image fusion, simulating the attention to the target and user experience evaluation. Similarly, the context of system environment can be modeled and processed to perform tasks including joint performance evaluation, devices authentication and system structure and operations with the support of context-based computing to cope with a set of circumstances during processing.

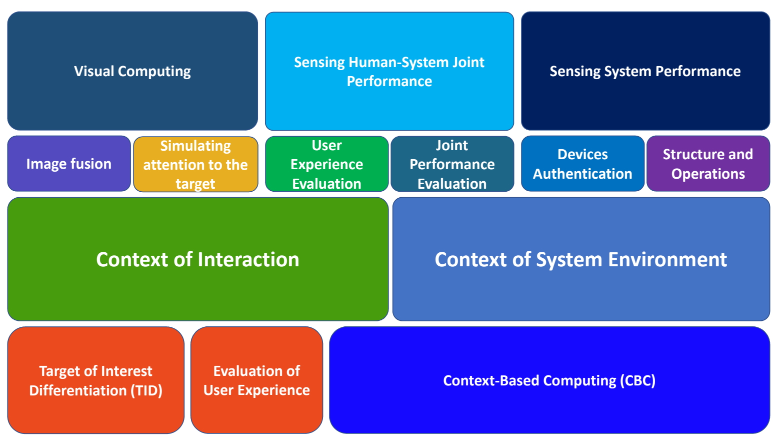


Figure 1.9: The enhancements required for collaborative agent-based information processing in iHCI

### 1.4.2 Limitations

Regarding each enhancement listed above, we break down the tasks in this section. As for the application of visual computing, this thesis is limited to the following tasks:

- L(1.1) simulating attention to the target, i.e., to distinguish the target in the scene and differentiate it from the other objects as a background, and
- L(1.2) image fusion, i.e., to synthesize the scene changing the background and to simulate the capability of a human mind that can fuse the target of interest in memory with another scene in imagination.

As for the sensing system performance, this thesis is limited to the following tasks:

- L(2.1) to perform the authentication to the devices to detect the well-intended malicious operations;
- L(2.2) to be aware of the structure and operations of the system for processing.

As for sensing human-system joint performance, the thesis is limited to the following tasks:

- L(3.1) to evaluate the user experience;
- L(3.2) to evaluate the joint system performance.

## 1.5 Supporting Methodology

Aiming at the tasks above, we define the methodology to support the corresponding functionality for each group tasks as follows:

(1) Target of Interest Differentiation (TID): to enable the system to detect the subject of interaction as a target of interest, as discussed in Chapters 5, 6 and 7;

(2) Context-Based Computing (CBC): to enable the system to process the set of circumstances or facts during interaction and processing of tasks for visual computing, as discussed in Chapters 4, 7, 9, and 10;

(3) Evaluation of User-Experience: to enable the system to process the experience of a user during a specific interaction, as discussed in Chapter 8.

The context in the context-based computing consists of two orientations (as show in Figure 1.10):

- Context of Interaction: the context of the scenario related to perception in real world that surrounds the subject in a particular event, situation, etc. as discussed in Chapters 4 and 7;

- Context of the System Environment: the context of the virtual-environment related to the devices, operations, and processes to perform the functionalities of the system as discussed in Chapters 9 and 10.

**Remark 3.** *The context-based computing refers to a general class of systems that can sense the physical environment, and adapt their behavior accordingly, which is not limited to mobile computing. In this thesis, we focus on context-based computing using computer vision and interactive systems.*

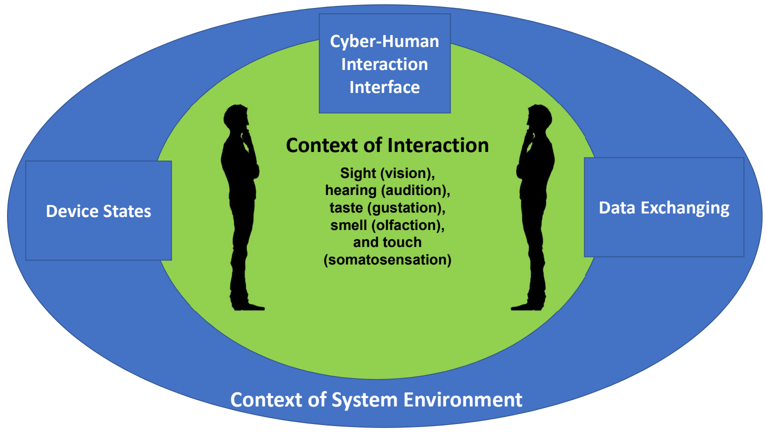


Figure 1.10: Context in a Cyber-Human Interactive System

We propose a number of visual computing methods. These methods are based on the way humans perceive information, which does not require heavy use of sensors, The proposed solution may help reduce the cost of MR systems and to alleviate the constraints on the implementation.

In some cases, interactions are not only related to the distance, but also the appearance (texture) of the subjects. Examples of this type of systems can be found in many applications (e.g., [219, 449, 478, 533, 592]). These applications execute processes in such a way that they operate by analyzing the captured appearance of the subjects. With visual computing, the system's dependence on the sensors is relieved.

This brings flexibility in system implementation. For example, participants would no longer need to wear a suit with many sensors and transmitters to communicate with the receivers in the virtual environment. The system response is delivered according to the visual information captured by either cameras or other optical sensing technologies (e.g., infrared sensors). Due to the reduction of sensors and the corresponding need for networking these, the interaction would be simplified by the use of camera systems with relatively less number of phases for calibration, networking and transmitting-receiving.

In the meantime, the number of the participants will not be limited by the number of devices or motion capture suits available anytime. The visual computing methods will also allow adding special effects to the simulation by reducing device dependence. Most modern mixed reality systems possess a subsystem for visual computing. Visual processing plays an integral part in mixed reality [405, 441], even though there are many other techniques used. We mainly focus on the simulation of human visual processing for mixed reality applications in this thesis. Techniques, such as enhanced matting [349], principal component analysis (PCA) [345], knowledge-based systems (KBS) [350], and collaborative information processing [351] are used to support the simulation of human visual processing and implementation of iHCI.

## 1.6 Research Questions and Implementation Issues

### 1.6.1 Research Questions

Based on the discussion above, we narrow the research down to several research questions, including:

(1) RQ 1: What are the major components of an iHCI framework for mixed reality?

(2) RQ 2: How can we simulate human's visual processing in iHCI to differentiate the target of interest in mixed reality?

(3) RQ 3: How can we design a knowledge-based information system to model human experience in mixed reality scene fusion?

(4) RQ 4: How can we optimize the processes to improve the joint performance of human and computer interaction in an iHCI system?

(5) RQ 5: How can we manage dispersed, distributed but collaborative information processing in an iHCI system using an agent-based system architecture?

(6) RQ 6: How can we guarantee the information security in an iHCI system for mixed reality?

The details about each research question are discussed under the heading of research issues below.

### 1.6.2 Research Issues

To answer the questions above with the development of an iHCI framework using collaborative agent-based information processing, one must solve following implementation problems:

(1) **System Design:** An iHCI system using collaborative agent-based information processing for mixed reality consists of a number of information systems as discussed in Chapter 4. Different from the complementary networks that people and organizations use to collect, filter, process, create and distribute data, an iHCI system for mixed reality must focus more on visual processing, as well as user experience and security to guarantee the reliability of the system. Related sub-questions to be answered here are:

- What are the main elements of the system?
- How integral are these elements?
- What are the aspects required to be enhanced?

(2) **Target of Interest:** Visualization is a key component of an MR, and computer vision and image processing can be used to simulate humans' visual sense in agent-based interaction. To interact intelligently, it is important for an iHCI system to detect the target of interest during the interaction. For an iHCI system, it is crucially important for the system to recognize targeted subjects, to model and process the patterns, and to perform the proactive interaction. An iHCI system must process the context in the scene, especially users, the relationships between them, and their environment. This requires the computer to be aware of the objects. By using the simulation of human visual processing in mixed reality, the system must be able to recognize an object as the target of

interest. Once the machine is aware of a target, visual processing can be used to differentiate between the useful details and the trivial uncertainty to preserve higher fidelity for mixed reality. However, as discussed in Chapters 5 - 7, how to enable a machine to be aware of what the target is and what not remains as an open issue. How well the interactions are between human and computer depends on the extent of the recognition (i.e., the target of interest), so do the processes for the computation.

(3) **Knowledge and Experience:** As discussed in Chapters 5, 7 and 8, in many cases, human knowledge is required for a computer to solve a problem. This makes the processes in iHCI more human-centered. This results in better user experience. However, user-experience and knowledge vary from user to user, as well as case to case. How to describe and introduce such knowledge and how to represent it in an iHCI framework is an important issue. In this thesis, we focus on the design of a knowledge system to simulate humans' visual processing and experience in iHCI for the target of interest recognition.

(4) **Quality of Experience and Quality of Service:** In information systems, it is necessary to ensure the value of the facility. As discussed in Chapter 8, since Quality of Experience (QoE) represents the Quality of Service (QoS) from the user's viewpoint, QoE is an extension of QoS. Given network quality, Quality of Service (QoS) supplies a sound basis for a system to provide a service. An iHCI system for mixed reality must

consider both the QoE for immersion experience and the QoS for system performance. However, usually, the resource for computation and communication is limited in mixed reality. This makes it difficult for QoE and QoS to reach the optimal levels concurrently. Therefore, how to manage QoE-QoS balance is a significant problem for next-generation network systems.

(5) **System Management:** As discussed in Chapter 9, with the consideration of remote applications and ubiquitous access to those, the knowledge used in an iHCI system could be distributed. Data processing is based on data dispatching via a networked data organization. Similarly, processing knowledge is also based on data dispatching via a networked dataflow. An iHCI system may be comprised of computing entities, such as sensors, actuators and processors, to collect and process data from different sources. For the distributed data update, the system may be scalable but run as a whole system in a batch of concurrent operations. How to manage the system to run efficiently becomes a significant issue for the performance and usability of the system.

(6) **Confidentiality and Security:** As discussed in Chapter 10, similar to computer systems, an iHCI system for mixed reality may also suffer from malicious attacks, especially if it is an open system. For example, a fraud node can be put into the system pretending as a sensor to spy the information during processing. This behavior poses a great threat to users'

privacy, especially for serious applications, such as military and medical systems. When some malfunction takes place, it is hard to locate the fault in the system accurately because numerous sensors are distributed in the system, particularly in the systems using a peer-to-peer architecture. As one of the most significant factors in data communication for mixed reality, one must take information security into consideration. We focus on the confidentiality of data communication and the security of the system, regarding authentication and encryption for access protocol and attacks. While guaranteeing the performance of information security, the efficiency of processing big data is also taken into consideration in this thesis.

## 1.7 Overview of the Thesis

The overview of the thesis has been demonstrated in Figure 1.11.

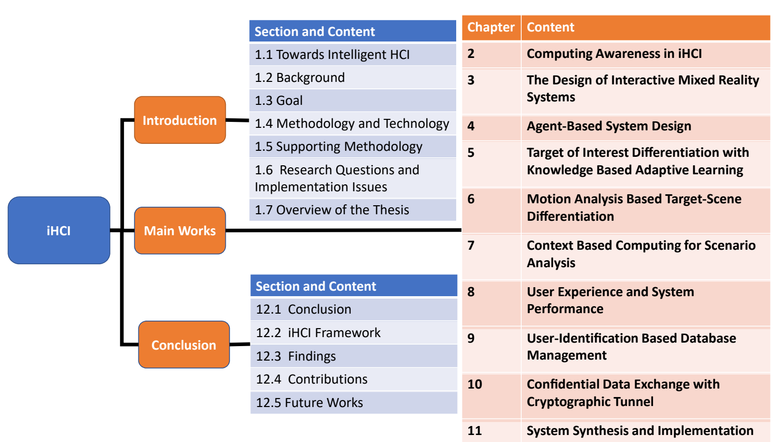


Figure 1.11: Overview of the Thesis Organization and Contents

Chapter 1 mainly introduces the research background, research problem, goals, research questions and overview of the thesis. The rest of this thesis is organized as follows. Chapter 2 presents a literature review on computational awareness by reviewing and discussing the related works covered in the methodology and technology used in this thesis.

Chapter 3 and 4 discuss the system design using collaborative information processing in an iHCI MIXER framework for mixed reality. In Chapter 3, the comprehensive HCI issues in VR, AR, and MR, have been discussed with a task analysis on mixed reality fusion, QoE-QoS management, confidentiality, and security in mixed reality. Systematic design of an information system for enhanced mixed reality interaction is given. The main concept of the mixed reality environment (MIXER) is introduced in detail. Related supportive modules for implementation are given. An agent-based design is presented in Chapter 4 with a discussion on the related issues and solutions to flexible access to different agent-based computing entities under a coordinated collaboration.

Chapter 5 to 7 address the issues of human experience, knowledge modeling and processing for target of interest. Three processing schemes for target of interest are presented in terms of semi-supervised analysis, motion analysis, and context analysis respectively.

Chapter 5 presents a matting scheme using human knowledge to perform visual differentiation. With the consideration of uncertainty, a recursive $\alpha$ optimization framework with fuzzy adaptive learning strategy has been proposed. The proposed scheme successfully applies human knowledge to target differentiation. The uncertainty of data and solution are both taken into consideration.

Chapter 6 presents a scheme based on motion analysis for target differentiation. An adaptive learning strategy is proposed based on Gaussian Modeling (GM) and kernel learning strategy. It helps the system adapt to the different background conditions and priori presumption of scene when recognizing the target of interest. Via an application in keying, it shows that the adaptive learning strategy can perform a layering task without the support of prior knowledge of the scene.

Chapter 7 presents a scheme for stereo pattern analysis using a pattern-context-based computing strategy. A knowledge based inference system is built using human knowledge to model the correlation of the context and processing. An enhanced learning approach is introduced to allow the system to process ambiguous patterns and to refine confidence. Experimental results show that the strategy allows the system to be aware of the uncertainty in the pattern. Thus, potential patterns can be differentiated and rebuilt as an extracted stereo model using the context-processing.

Chapter 8 presents a scheme to model user experience and to reach the optimal balance between QoE and QoS management. Based on visual computing techniques, the issue of user experience is further explored. A data-aware QoE model is built based on Principal Component Analysis (PCA), and a data-aware QoE-QoS unified optimization is also presented in a normalized scale space for

QoE and QoS balance. The normalization here means adjusting QoS and QoE values measured on different scales to a notional scale, so that brings them into alignment for computation.

Chapter 9 presents the solution to perform the scalable learning for dispersed knowledge systems. A scalable learning scheme and $\xi$ process are proposed with related theoretical analysis. With the proposed scheme, a dispersed knowledge architecture can be used as a modular centralized system without updating the entire database.

Chapter 10 presents the main requirements for security in sensor network subsystem (SNS). A Wireless Sensor Media Network (WSMN) is taken as an example for SNS. A data-aware scheme is proposed to perform the processing of system with the security enhancement for confidential communication by using a public key cryptography based attack detection approach. Experimental results show that the scheme is able to protect the system against both the impersonal intrusion and key recovery attack simultaneously using a data-aware attack-detection strategy.

Chapter 11 presents a iHCI framework using a information system for MR applications, and discusses the system design and implementation in terms of functionality, modules and work flow. Related modules along with their functions and test results are presented and discussed in Chapter 11. The test results demonstrate the feasibility of the proposed collaborative agent-based information processing scheme.

Chapter 12 evaluates the thesis, draws conclusions and present findings and contributions as well as limitations and future work. The chapter summarizes the answer to each research question listed in Chapter 1 and contributions of the thesis involve in system design, target of interest, human knowledge and user-experience, QoE-QoS management, system management and confidentiality and security.

The logic of the thesis, regarding the enhancements required as discussed in Section 1.4.1, research questions (RQ), limitations, related methods, chapters and publications, are shown in Table 1.3. The relevant publications are listed below,

(1) C.Z. Liu, M. Kavakli, **Mixed Reality with a Collaborative Information System**, Proceedings of Asia-Pacific Services Computing Conference (Zhangjiajie, China, Nov 16 - 18, 2016), pp. 205-219, Springer, pp. 205-219, 2016. [351]

(2) C.Z. Liu, M. Kavakli, **An Agent-Based Collaborative Information Processing System for Mixed Reality Applications Part A: Agent-Aware Computing**, Proceedings of IEEE Conference on Industrial Electronics and Applications (Wuhan, China, May 31 - Jun. 2), IEEE, 2018, accepted. [355]

(3) C.Z. Liu, M. Kavakli, **An Agent-Based Collaborative Information Processing System for Mixed Reality Applications Part B: Agent-Based Collaborative Information Processing and Coordination**,

Proceedings of IEEE Conference on Industrial Electronics and Applications (Wuhan, China, May 31 - Jun. 2), IEEE, 2018, accepted. [356]

(4) C. Z. Liu,M. Kavakli, **Knowledge Based Adaptive Fuzzy Strategy for Target of Interest Differentiation with Its Application in Enhanced Matting**, Submitted to Elsevier. [357]

(5) C.Z. Liu, M. Kavakli, S. MacCallum and L. Hamey, **Motion-keying Based Dynamical Scene Layering with Adaptive Learning**. Proceedings of International Conference on Computer and Automation Engineering (Sydney, Australia, Feb. 17-21), ACM, pp.no. 111-115, 2017. [360]

(6) C.Z. Liu, M. Kavakli, **Knowledge Based Pattern-Context-Aware Stereo Analysis and Its Applications**. Proceedings of The International Conference on Digital Image Computing: Techniques and Applications (Gold Coast, Australia, Nov. 30 - Dec. 2), IEEE, pp.164-171, 2016. [350]

(7) C.Z. Liu, M. Kavakli, **Extensions of Principal Component Analysis with Applications on Vision Based Computing**, Multimedia Tools and Application (Hefei, China, Jun. 5-7), Springer Germany, vol. 75(17), pp. 10113-10151, 2016. [348]

(8) C.Z. Liu, M. Kavakli, **Data-Aware Quality of Experience - Quality of Service Management**. Proceedings of IEEE Conference on Industrial

Electronics and Applications (Hefei, China, Jun. 5-7), IEEE, pp. 1823-1828, 2016. [346]

(9) C.Z. Liu, M. Kavakli, **Scalable Learning for Dispersed Knowledge Systems**, Proceeding of Annual International Conference on Mobile and Ubiquitous Systems: Computing, Networking and Services (Zhangjiajie, China, Jul. 20), ACM, pp. 125-134, 2016. [352]

(10) C.Z. Liu, M. Kavakli, **A Data-Aware Confidential Tunnel for Wireless Sensor Media Networks** Multimedia Tools and Application, Springer Germany, pp. 1-23, 2017. [353]

(11) C.Z. Liu, Hasan Alyamani, M. Kavakli, **Behavior-Intention Analysis and Human-Aware Computing: Case Study and Discussion** Proceedings of IEEE Conference on Industrial Electronics and Applications (Singapore, Jun. 18-20), IEEE, 2017, in press. [344]

(12) C.Z. Liu, M. Kavakli, **An Intelligent HCI Framework Using Agent-Based Computing in Mixed Reality** The International Journal of Virtual Reality, vol. 17 (03), pp. 1-14, 2017. [354]

in which the publications placed in the thesis can be categorized into four parts:

(1) system design, including publication 1, 12, 2, 3;

(2) literature survey, including publication 7

(3) algorithm/method development and analytical analysis of the proposed method, including publication 4, 5, 6, 9, 8,and 10,

(4) case study, including 11.

The details are given and discussed in the following chapters.

Table 1.3: The Logic of the Thesis (RQ for research questions, VC for Visual Computing, TID for target of interest differentiation, CBC for context-based computing, EUE for evaluation of user-experience)

| Enhancements | Limitations | RQ | Methods | Chapters | Publications |
|---|---|---|---|---|---|
| 1 $VC$ | $L1.1$<br>$L1.2$ | $RQ2$<br>$RQ3$ | $TID$<br>$EUE$ | 5, 6, 7,<br>8, 3, 11 | 4, 5, 6,<br>8, 1, 12 |
| 2 $SSP$ | $L2.1$<br>$L2.2$ | $RQ1$<br>$RQ5$<br>$RQ6$ | $CBC$ | 3, 4, 9,<br>10, 11 | 1, 2, 3, 9,<br>7, 10, 12 |
| 3 $SHSP$ | $L3.1$<br>$L3.2$ | $RQ4$ | $TID$<br>$EUE$ | 3, 8, 11 | 8, 1, 11,<br>7, 12 |

# Chapter 2

# Computing Awareness in iHCI

## 2.1 Introduction

In this chapter, we review the existing works as a preparation for design and implementation of an intelligent human-computer interaction (iHCI) system and computing various types of awareness. By reviewing the works related to computing awareness, we discuss its origin, definition, and extensions. According to the existing works, the awareness in computing can be mainly categorized into three main groups, including:

- target-awareness,
- self-awareness and
- context awareness.

As shown in Figure 2.1, we also review the concepts of:

- human-aware computing,
- user-aware computing,
- data-aware computing and
- agent-aware computing

as well as the relations in between.


Figure 2.1: A Computational Awareness schema

Computing awareness is important for an iHCI system. Inspired by the social scientists, philosophers, and anthropologists, a possible way to embody smartness in HCI is to make systems have human-like awareness to understand the situation in the interaction [83, 94, 259, 549, 654, 665].

Awareness refers to the ability to know that something exists, or to understand a situation or subject based on the information or experience. The concept of "being aware of" is defined as having knowledge or experience of a particular thing, or people that exists [141, 151, 243, 254]. This type of awareness is complex to model but can be used in HCI systems [682].

Chakraborty et al. [94] studied awareness and perception in human brain and developed a novel method to interpret underlying mechanisms of awareness with a three-valued logic model $\{y, x, C\}, y \in \{-1, 0, 1\}$, where if the output awareness output $y$ is 1, the perception input $x$ definitely belongs to a certain concept $C$; if $y$ is -1, $x$ definitely does not belong to $C$; if $y$ is 0, the subsystem cannot make the decision. They pointed out that computational awareness has potential impact on many applications in finance, economics, public health and environmental science. There are still many theoretical and practical challenges to address related to collective social behavior, dynamics of opinion, stability of service, sustainable use of resources, security and reliability of infrastructure.

More recent research [682] suggests that HCI systems need to perceive, reflect, act, and communicate with respect to time or space.

## 2.2 Challenges in Computing Awareness

In their seminal paper [682], Ziemke et al. proposed six challenges in the development of the computing awareness. These are related to:

(1) disparate data in less consistent models,

(2) data selection with active information acquisition,

(3) intelligent inference among the elements of the situation,

(4) assessment of uncertainties associated with data, information, predictions and decisions,

(5) decision-making to act based on goals and objectives,

(6) optimization of decision-making to achieve shared situation awareness with agents.

It can be seen that

- challenge (1) refers to addressing research question RQ 1 regarding the iHCI framework and the system architecture, as well as research question RQ 5 regarding database management and information processing for flexible access in a distributed structure;

- challenge (2) refers to the research question RQ 2 regarding the target of interest differentiation as well as the research question RQ 3 regarding the information processing methodology;

- challenge (3) refers to research question RQ 2 regarding awareness for inference;

- challenge (4) refers to research question RQ 2 addressing the interference caused by uncertainties;

- challenge (5) refers to research question RQ 6 regarding goal oriented decision-making and operations;

- challenge (6) refers to research question RQ 4 regarding optimization of interaction as well as research question 5 regarding the coordination among agents.

### 2.2.1 Context-Aware Architectures

Some preliminary work was carried out in the early 2000s. Ye et al. studied group awareness in collaboration with the consideration of the situation in the work [654]. They proposed the concept of smart distance and drew our attention to social contexts with the preservation of users' privacy in a distributed collaborative environment. The work shows that a sense of group presence can be created by using an agent based architecture. Based on Open System Interconnection (OSI), Zhang et al. modeled context awareness as four layers of functionality for communication-oriented computing, including representation layer, aggregation layer, context layer and utilization layer [665]. They presented a context-aware service architecture for smart homes with the integration of a temporal ontology and reasoning based on semantic web technologies in context modeling.

In addition to context awareness, recently, desired efficacy using IoT has also been taken into account. Many attempts have been made [83, 259] with the purpose of energy efficiency. Jahn et al. [259] developed a smart home system considering energy efficiency features. With a peer-to-peer network, common devices in households had been connected and energy consumption data was obtained by wireless power metering devices (smart meters). They pointed out that interaction techniques help to build up awareness of situation by intuitive user interfaces presenting the data in meaningful contexts, allowing end users to gain access to the information of concern and interact with their environment. Byun et al. used smart grid technology and questioned effectiveness of such implementations in homes and buildings [83]. Considering the architectural limitations, they proposed novel system architectures for smart energy distribution and management using renewable energy systems and electric power controls. User patterns were taken into the consideration in the design as well. By using context awareness in a smart energy distribution, monitoring and control system, the system was able to reduce service response time and the power consumption, while monitoring information about power consumption.

The main limitation of those studies for iHCI is that they fail to consider human factors (e.g., user-experience) in HCI, while addressing technological needs. Although most of them were focusing on user-oriented applications, and some works (e.g., [83,259,654]) even mentioned user-related factors such as privacy, user-interface, and interaction technologies, research focused more on inter-operation of systems rather than user interaction and user-experience.

### 2.2.2 Embodied Computational Awareness

Computing awareness is a necessary extension to create an iHCI system with states or ability to perceive, feel, or be conscious of systems that are aware [191, 481]. Computational awareness has diverse meanings. Awareness of related environments, users and associated devices, and systems changes in varies applications. There may be gaps to fill in between different types of awareness required for both processing and modeling.

Even though the relationship between sense and awareness is complicated, sense is essential to simulate awareness [387,391]. To enable machine sense, many sensors are required [1]. By capturing the measurements through sensors, particular types of computational awareness can be modeled and specified [228,239,626], especially using IoT (Internet of Things). We call this embedded computational awareness.

In their paper [239], Hong and Landay showed that sensors serve as an infrastructure for context awareness in computing. They stated that sensor networks can be scalable by adding the appropriate sensors and corresponding widgets connected to the sensors. They pointed out that reliability of sensor data serves as an important factor to form the context of the whole environment.

Wang et al. suggested to use a vehicular sensor network (VSN) for metropolitan air quality monitoring [626]. They used cars as carriers equipped with gas sensors, GPS receivers, and wireless interfaces such as WiFi and LTE-A. GPS receivers provide location data; gas sensors provide air quality data. With the data-fusion, the whole air quality map of the city can be represented, and the performance of mapping mainly depends on the accuracy of the location.

Hazas et al. studied different sensors-based systems for location-aware computing [228]. Focusing on the issue of the determination of physical location, they drew a distinction between different location-sensing technologies, such as RFID, GPS, and WiFi, and classified the deployment in three main types of systems, i.e., research lab systems, custom-systems and consumer-systems. It has been demonstrated in their research that consumer systems usually need high location accuracy, and most location-sensing technologies can only guarantee the accuracy within ten meters.

Different sensors have various capabilities as well as limits. Sensors that detect some characteristics of the physical environment and respond to those measurements have physical limits due to the range of the physical measurements, such as moisture, pressure, temperature, light and sound (e.g., [414, 639, 643]). Meanwhile, the transceiver of a sensor has limitations due to the physical measurements (e.g., radio communication, electronic wave) [144,198,558]. In an iHCI system, to detect a targeted subject and its motion, depth detectors can be used to measure the distance to its position. Usually, the range of a typical distance detector is around 5-10 meters. Any object beyond this range would not be detected. This limits their usability in iHCI systems. However, humans sense the environment and the physical world differently compared to sensors [94, 480]. As for depth and position measurement, for example, humans perceive the target with a depth of field sensor using vision as well as spatial knowledge. This is different from a depth detector with infrared or time-of-flight measurements. The typical range of human vision is approximately ten times more than the depth detector (further than 50-100 meter). Therefore, there is a need to integrate this spatial knowledge with the sensors.

## 2.3 Computational Awareness in iHCI

In an iHCI system, computational awareness does not necessarily imply full understanding of the context or total comprehension, but it can be simplified as a type of sense or vigilance in observing, or alertness in drawing inferences from what it experiences. By simulating fundamental abilities for living beings to survive, computing awareness can bring computation closer towards the goals of computational intelligence (CI) or artificial intelligence (AI) make the system more efficient [34, 100, 370]. Considering the design of iHCI systems, in this thesis we focus on three main types of awareness are introduced in the research, including:

(1) target-awareness, a system that is aware of what is the target of interest;

(2) self-awareness, a system that is aware of itself and its states in operation;

(3) context-awareness, a system that is aware of its surroundings and inter-operations including itself, users, environment, and what happens during the interaction.

### 2.3.1 Target-Awareness

Target-awareness refers to the realization of being aware of a target [203, 227, 293, 339, 470]. If the target is a user, then target-awareness becomes user-awareness. The main task of this type of awareness computing is to detect and recognize a targeted object and deliver a desired response correspondingly [203, 339].

A target-aware system, must execute necessary actions to achieve a specific goal based on the recognition of the target. In practice, some systems mainly focus on the non-human aspect of computational awareness (such as location [203], and distance [227, 459]) to perform tasks, whereas some systems form the awareness using visual data (e.g., gaze image [293]). When there is interference in the data, a target-aware system must distinguish the target-of-interest (TOI) out from the trivial uncertainties (i.e., target-of-interest differentiation [350]). To bridge the gap between sensor-based computational awareness and natural human awareness, human knowledge and experience can be utilized to improve. Processes by shedding of irrelevant possibilities and preserving more trustworthy information [6, 350]. How to model target awareness in a computational form and how to address the uncertainties in differentiation are main issues target-awareness. In this thesis, we mainly focus on the vision based target-awareness models and corresponding computation for differentiating the target-of-interest with the consideration of uncertainties, as demonstrated in Chapters 5, 6, 7,and 11 [350, 357, 360].

### 2.3.2 Self-Awareness

Self-awareness originally involves a psychological concept related to the capacity for introspection [45,542,601]. It refers to an ability of a subject to recognize oneself as an individual separate from the surroundings and other individuals. In addition to its roots in psychology, the notion of self-awareness has been used in computing [130, 266, 332, 377, 481].

For the applications of intelligent systems, self-awareness can be specified as self-reflection, self-prediction, and self-adaption [266].

- Self-reflection refers to the awareness of the operating conditions, such as the system architecture, execution environment, and the authentication infrastructure; the self-reflective awareness also aims at the operational goals including quality of service (QoS) requirements [135, 336], cost [25, 208] and energy-efficiency [237, 313], etc., as well as the influence of dynamic changes on the above system performance during operation [331, 332].

- Self-prediction mainly focus on the ability of the system to predict dynamic changes and their effect on the performance, such as service workloads [427, 535, 616], and QoS requirements [35, 135, 336]. In some cases, the prediction also needs to take the effect of possible response and desired actions (e.g., service deployment [373], load balance [96], resource allocations [200], etc.) into consideration for intelligent applications.

- Self-adaption mainly refers to the system's ability adapt to the conditions, situations and their changes to guarantee the goal related to self-reflection [10, 96, 466].

Most of these works reflect computing self-awareness to certain extent, however, they mainly focus on system performance and dynamics. In an iHCI system, user-experience should be taken into consideration as well, but studies for focusing on user-experience are still rare. In some cases, when self-awareness is required (especially, in a wide area inter-operation), decentralization is the approach account taken for the system to obtain a better sense of self-awareness, using the information other local surroundings or of constituent elements in the system [377]. This study mainly focuses on adaptive system operation as demonstrated in Chapters 5, 6, 7( [350,357,360]), 4 ( [355,356]), 9 ( [352]), user-experience and quality of service (QoS) in Chapter 8 ( [346]) and information security in Chapter 10 ( [353]).

### 2.3.3 Context Awareness

The context in computing refers to the environment, conditions and surroundings where the subject of interest and its processing are in [191, 239]. The goal of context-aware computing is to offer relevant information and/or services to a user by capturing the contextual information in a dynamics situation, the status of a device, or the surroundings [39, 239]. Context, such as time, identity, place, conditions can be used to model context awareness to influence processing and system performance. For example, by being aware of the time, systems can coordinate operations adaptively to reach the desired service [373]. Being aware of user identity, computers can personalize a user interface [632], the corresponding data storage [220, 615], operation [142] and management [250, 361]. Various types of context can be combined to develop pervasive computing systems [522]. Examples can be found in both human-context [134, 211, 614] and business-context [435, 497] that present many ways of organizing and applying information generated in real-time.

Similar to self-awareness, studies of context-awareness must also take uncertainty, dynamical changes and decentralization into consideration [44, 139, 211, 570]. However, it emphasizes the computing entity's consciousness of its surroundings and the environment rather than the targeted object or itself. If the computing entity is the targeted object, then the context-awareness takes the form of self-awareness. In other words, context awareness include target-awareness as well as self-awareness.

Due to the development of intelligent communication systems for ubiquitous network [247,322,341], research studies on cognitive radio [14,411,432] and mobile computing [5, 307], investigate context awareness in communications. In this case, context awareness refers to a property of mobile devices and network, regarding location (e.g, [9]), linking changes (e.g, [189]), and other communication resources (e.g, [85]), which is complementary to consciousness of the environment. In this thesis, we investigate context awareness in Chapters 7 and 4 ( [350, 355, 356]).

Aiming at an iHCI framework, we focus our research on the original concept of target-awareness, self-awareness, and context-awareness, leading to intelligent computing of a system using the knowledge of diverse targets, systems and context. Therefore, computing awareness must be extended to include definitions of human-aware computing, user-aware computing, data-aware computing and agent-aware computing as well. In the following sections, we will define these concepts under the subtitle of extended computing awareness.

## 2.4 Extended Computing Awareness

### 2.4.1 Human-Aware Computing and User-Aware Computing

Human-aware computing can be seen as an extended example of the target-awareness computing and context-awareness computing [67, 351, 545, 681]. The components in a human-aware computing model work together as an autonomous computing entity to perceive, feel, and be conscious of events, objects, or sensory patterns for human-centric inter-operations. This autonomous entity, like a human, perceives its surroundings and then acts to perform human-oriented tasks. The actions affect the environment and the changes of the surrounding lead to further actions for a specific goal. The target in this case is a human, and the context is mainly human-context(e.g., [615]). By perceiving and acting, target-awareness and context-awareness are formed to model the perception and action of the system as a close cycle. With this logic model, the system is able to assess and the human behaviors and adapt to the changes of context with the update of the awareness continuously. To react correspondingly, knowledge of anthropomorphism in psychology [149, 164], is required for modeling computational awareness with the perception-action cycle and corresponding stimulations for triggering the interaction actuators in the system.

User-aware computing is a particular case of human-aware computing. The overlapping section of user-aware computing with human-aware computing is when the human is user of the HCI system [86, 382]. In this thesis, Chapter 3 applies human-aware computing in the mixed reality environment design. Self-awareness may be regarded to adjust the system's states, and data can be used to bridge the gap between different entities and operations, which leads to the extension to data-aware computing.

### 2.4.2 Data-Aware Computing

Data-aware computing can be seen as an application of self-awareness computing and context-awareness computing. It refers to a system or computation that optimizes itself and its processing based on the data, which identifies itself to perform the task consciously(e.g., [175, 589, 666]. Data-aware computing is the computing based on self-awareness and context-awareness when the awareness is modeled in data representation. With the features of data, data awareness can be built as a conceptual recognition of a set of classified representation for different targeted operations [38, 110, 299, 303]. Correspondingly, the different command executions are classified as contextual command applications, creating an automatic binding to current situation in a system-level by the feature obtained by data analysis that involves the available resource and conditions. With the results of analysis, reasoning leads the system to adopt data-triggered actions based on the classified operations. Essentially, data-aware computing is a particular case of computing awareness.

By emphasizing more on data-representation and data-modeling, data-aware computing can be performed without complete knowledge about the system, and the operations can be modeled as a set of procedures based on data analysis and representation. In this thesis, Chapters 8 and 10 focus on data-aware computing and its applications [346, 353].

### 2.4.3 Agent-Aware Computing

Agent-aware computing can be seen as an extension of the computing of target-awareness, self-awareness and context-awareness, where the computing entities are abstracted as a set of agent-based model (ABM [196, 232]). Each agent refers to an autonomous entity that acts accordingly upon an environment for a specific task [450, 453, 638]. In a HCI, it can be either a human agent or a computerized agent, such as a machinery, a piece of software or a robot, to perform specific processing for a user or another program [183, 267, 439]. All agents play their parts to form a collective effect in the group to perform a specific task [48, 82, 109].

Agent awareness can be modeled as beliefs for action and the situations. Forming highly weighted belief(s) and intents, agents can act motivated by the observation [365, 636]. Corresponding awareness computing can be implemented by using agent-based intelligence that includes task-oriented methodical behavior, functionalities, procedural approaches, algorithms, or reinforcement [267, 421, 450]. Related issues, such as knowledge representation [70, 555], autonomous agents [374, 375], and agent coupling and coordination [257, 640], had been proposed and discussed with corresponding solutions. Intelligent capabilities of agent-based systems, such as perception (e.g., [236,611]), cognition (e.g., [60,88]), observation (e.g., [27,575]), recognition (e.g., [241,378]), and instruction(e.g., [167,181]), had been developed to support the implementation of agent-based iHCI systems. In this thesis, Chapter 4 computational agent-based awareness models [355, 356].

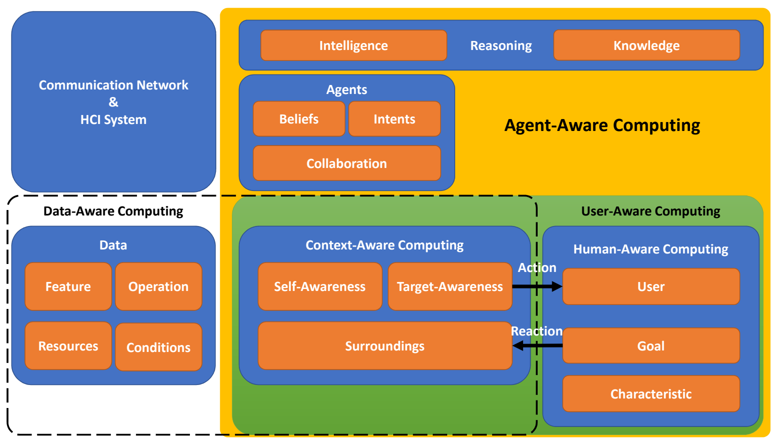


Figure 2.2: A Computational Awareness Model

Figure 2.2 shows the computational awareness model. This model can be seen as a multi-agent system, which can be used to perform agent-based collaborative information processing.

## 2.5 Agent-Based Collaborative Information Processing

For computing awareness in iHCI, a system may require a large number of computing entities, such as sensors, actuators and processors, to collect and process the information about the users, data and itself [199, 395, 606]. Processing is difficult due to the number of distinct entities [240, 353]. The system may consists of diverse individual entities, components or sub-systems, and they vary from each other in terms of capabilities, capacity or behavior [33, 56]. Therefore, the structure of the system is complex and the logic between these constituent parts of the system is less centralized. Consequently, the system performance would be affected by the scale, heterogeneity and system structure issues [281, 418].

A multi-agent system (MAS) with collaborative information processing can be used to provide a feasible solution to these issues. MAS refers to a system that consists of multiple agents within the environment. By interactive operations, it can perform tasks that are complex for a single agent to complete [53, 174, 600]. Rather than a monolithic system, a MAS emphasizes collaboration and coordination among the agents [409]. The task performance is seen as a result of collective behavior of all agents in the group. One of the applications of MAS is to perform collaborative information processing tasks, which processes and coordinates the information from diverse sources in cooperation(e.g., [587]). Collaborates information processing can be implemented by using both distributed and centralized modes [583]. Many related studies state that selection of a proper collective behavior emerging from different computing entities is beneficial to intelligent system design [292, 335, 369, 498, 512]. To determine this collective behavior, usually the system requires a particular coordination protocol for applications [87, 439]. An Agent-Based Model (ABM) is often used as a computational modeling methodology for analyzing and simulating the actions and interactions of the individual agents. These provide a blueprint of a systematic architecture for MAS [305, 315, 537]. ABM can be used in many applications, such as manufacturing [376, 538, 673], enterprize management [453], e-commerce [325], disaster management [194, 294, 530] and organizational behavior analysis [197]. In engineering, it mainly focuses on the explanatory logics with an insight into the cooperative behavior of agents under certain conditions or rules. Issues related to intelligent systems, such as knowledge representation [70, 555], autonomous agents [374, 375], and agent coupling and coordination [257, 640], had been proposed and discussed with corresponding solutions. In this thesis, Chapter 4 addresses agent-based collaborative information processing [355, 356].

## 2.6 Summary

This chapter mainly reviews the existing works related to computing awareness. The relations between computing awareness and intelligent human-computer interaction (HCI), the original concepts and extensions of computing awareness have been discussed. Computing awareness enables a computational system to perceive, feel, or be conscious of itself, target or surroundings (context). By modeling the awareness with a set of analytical states and a meta-state (a state of those states, e.g., belief), the computing entities with awareness can perform intelligent interaction as a live and functional being from a set of procedural commands execution. This serves as the fundamental concept and theoretical base for using the agent-based collaborative information processing for an iHCI framework. When modeling the computing entities as agents with awareness, the task of information processing can be implemented by using a collaborative strategy to complete comprehensive tasks in a flexible structure. This concept refers to the development of an agent-based collaborative information processing algorithms using computational awareness in iHCI.

The iHCI framework is mainly addressed in Chapter 3.

# Chapter 3

# The Design of Interactive Mixed Reality Systems

## 3.1 Introduction

This chapter focuses on the research question RQ 1: What are the major components of an iHCI framework for mixed reality? and presents a systematic design of an information system for enhanced mixed reality interaction. Based on the collaborative information processing system structure, we propose using an agent-based model as the system architecture; the main functionalities of the mixed reality environment (MIXER) are Mixed Reality Fusion (MRF), QoE-QoS management, and information security [351].

Primary components are 1) an agent-based system, 2) mixed interaction, 3) human-aware computing, 4) intelligent database management, 5) QoE-QoS management, and 6) information security and privacy management. These components are designed and implemented by using supportive modules, including:

(1) agents and collaborative information processing in agent-based systems [355, 356],

(2) mixed reality fusion in mixed interaction [351, 354],

(3) context-pattern analysis in human-aware computing [350, 354],

(4) collaborative user-identification based database management in data management [348, 352, 354, 356],

(5) user-experience and system performance coordination in QoE-QoS management [346, 354],

(6) cryptography and authentication in information security and privacy management [353, 354].

The corresponding supportive modules for the implementation are discussed along with their functionalities. The details are given in Chapters 4-10.ss

## 3.2 System Design and Framework

Pages 58-71 of this thesis have been removed as they contain published material. Please refer to the following citation for details of the article contained in these pages.

Liu, C. Z., & Kavakli, M. (2016). Mixed Reality with a Collaborative Information System. In Wang G., Han Y., Martínez Pérez G. (eds) *Advances in Services Computing. APSCC 2016*. Lecture Notes in Computer Science, vol 10065. Springer, Cham, p. 205-219.

DOI: 10.1007/978-3-319-49178-3_16

## 3.3 Discussion and Summary

This chapter mainly presented the architecture of a mixed reality environment (MIXER). Using the example of military tactic training, the MIXER design concept has been introduced in detail, with discussion on its flexibility and cost for applications. Solutions for related research issues, including human aware computing, mixed reality fusion, agent-based systems, collaborative scalable learning in distributed systems, QoE-QoS balance, and information security have been discussed. The necessity of the enhancements in iHCI has been emphasised; the main functionalities to enhance the system design, such as MRF, QoE-QoS management, and information security, have been proposed in a modular architecture. We apply agent-based design to implement various enhancements, such as human-aware computing, database management, and privacy management for mixed reality. The corresponding components for the implementation are presented with the iHCI system design. The next chapter covers an agent-based system design model to perform collaborative information processing, in order to implement the iHCI framework with the enhancements for the mixed reality system.

# Chapter 4

# Agent-Based System Design

## 4.1 Introduction

With an aim to answer the research questions, RQ 1 What are the major components of an iHCI framework for mixed reality? and RQ 5 How can we manage dispersed, distributed but collaborative information processing in an iHCI system using an agent-based system architecture?, this chapter mainly presents an agent-based system design. To implement iHCI, an agent-aware computing (AAC) concept is introduced. Related functionalities and tasks for agent-based modeling are discussed [355]. The design of agents, agent groups, and mixed agents are also given, and system organisation, processing, and collaboration are explained [356].

## 4.2 System Design and Framework

Pages 75-86 of this thesis have been removed as they contain published material. Please refer to the following citations for details of the articles contained in these pages.

Liu, C. Z., & Kavakli, M. (2018). An agent-based collaborative information processing system for mixed reality applications — Part A: Agent-aware computing. in *2018 13th IEEE Conference on Industrial Electronics and Applications (ICIEA)*, p. 1273-1278.

DOI: 10.1109/ICIEA.2018.8397905

Liu, C. Z., & Kavakli, M. (2018). An agent-based collaborative information processing system for mixed reality applications — Part B: Agent-based collaborative information processing and coordination. in 2018 13th IEEE Conference on Industrial Electronics and Applications (ICIEA), p. 633-638.

DOI: 10.1109/ICIEA.2018.8397792

## 4.3 Summary

This chapter mainly presented the details of an agent-based system for collaborative information processing to be used in an iHCI system. Task analysis has been used to specify the functionalities of the system based on the system architecture presented in Chapter 3. The components of the proposed agent-based system design and agent-aware-computing for mixed reality applications have been further illustrated [355]. A functional framework of the iHCI system, along with different types of agents and mixed agent groups, has been discussed [356]. By using the agent-based access and resource management and adaptive logical topology scheduling, the system can be organised flexibly for specific processing. Based on the collaborative information system architecture, the organisation strategy is presented for different functionalities. Identified issues include concurrent transaction coordination, serialisable scheduling, and overlapping conflict. To deal with the concurrent coordination, a two-phase locking strategy is applied. With the support of agents and groups, the main functionalities to enhance the system mainly focus on MRF, coordinative collaboration, system confidentiality, and QoE-QoS management. The following chapters will provide the details of the supportive modules for each functionality.

# Chapter 5

# Target of Interest Differentiation with Knowledge Based Adaptive Learning

## 5.1 Introduction

In this chapter, we focus on the issue of simulating human sight to differentiate the target of interest (ToI). With an aim to answer research question RQ 2 How can we simulate human's visual processing in iHCI to differentiate the target of interest in mixed reality?, a recursive learning strategy with fuzzy adaptive $\alpha$ vision vision update is proposed to enhance the visual computing to cope with the uncertainty of visual data and refine the details in the target differentiation. In order to answer the research question RQ 3 How can we design a knowledge-based information system to model human experience in mixed reality scene fusion?, we design a fuzzy knowledge and inference system using human expertise and user experience.

One method we use to differentiate the target in various images is to model the task as an object-matting problem [476]. The purpose of the task is to extract targeted objects in the image as the foreground, with all other information as the background; trimap is one of the most effective techniques to provide the foreground and background knowledge for matting [116].

In trimaps, there are always regions of indiscernibility between foreground and background [328] and these uncertain pixels create trimap-based matting difficulties in handling the uncertain anonymous pixels [229]. Two main methods to deal with the uncertain anonymous pixels are sampling-based matting (e.g., [116, 572, 620]) and propagation-based matting (e.g., [328, 619, 678]). The key to optimal matting lies in the constraints given by the labeled regions for uncertainty processing. However, due to the lack of discipline for obtaining the perfect trimap, which causes the uncertainty in matting, the stability and uniqueness of the solution can hardly be guaranteed in most cases.

Another option to reduce the uncertainty is based on techniques that enhance the condition of photography (e.g. [573, 622, 652]). Many variations on this type of strategy need special equipment or extra requests on the imaging. In addition to the cost, the uniqueness of the solution cannot be guaranteed, even if the trimaps obtained are the same quality, because most processing methods focus on different cases of local smoothness and linear characteristics in colour space [116, 229, 329, 572]. Many existing studies have aimed at performing matting with minimal residuals (e.g., [328, 534, 620, 678]), but reported suboptimal results due to the uncertainty of matting conditions [534, 619]. Therefore, solutions produced by different methods vary in uncertainty under various conditions and initial priori.

In order to address the issues above, we introduce human expertise and experience into the system to provide greater clarity in the uncertain regions. We model the experiences of different types of users, including professional graphic designers, amateur photographers, and laymen. With the help of the model, the fuzzy knowledge base and logic inference are used to assess the uncertainty in the captured data and processes applied. Fuzzy logic [298, 509, 663] is an efficient method to convert human knowledge into computational logic, and can be used in image processing (e.g., [287, 424, 597]). With this type of logic, a fuzzy system can perform reasoning with coded knowledge [276, 541, 582], which serves as an efficient method to deal with uncertainty in the process. (e.g., [338,400,596]). It is preferable to use fuzzy systems to process uncertain pixels in matting with adaptive a priori acquisition due to the ability to update the knowledge with a dynamic learning process and handle uncertainty with little prior reference (e.g., [92, 113]).

To introduce the human experience into the computation, we build the mathematical model of the uncertainties in the conventional matting formulation.

By analysing the relationship between the optimal solution and the uncertainties, we build a knowledge system utilising the experience of graphic designers. The knowledge is converted into computational logic with fuzzy modeling. Applying this knowledge in the fuzzy expert system, we design an adaptive learning strategy that considers the uncertainties involved in the knowledge. Anonymous pixels cannot be taken as noise, therefore we design an adaptive learning strategy to deal with the uncertainty. The assessment, based on the fuzzy knowledge system and adaptive learning strategy, provides the foundation for classifying any unidentifiable details [357]. Several principles to design a recursive strategy are proposed, and the convergence of the algorithm is discussed and proved to guarantee the optimal solution. This iterative knowledge updating and learning serve as a part of target-aware-computing to support the MRF, and matting is used as a showcase to demonstrate the feasibility of the algorithm. This chapter covers the experimental results, which demonstrate the effect of the proposed method, and a performance evaluation.

## 5.2 Fuzzy Knowledge Based Enhanced Matting with Adaptive Learning

# Knowledge Based Adaptive Fuzzy Strategy for Target of Interest Differentiation with Its Application in Enhanced Matting

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**Abstract**

In this paper, we present a fuzzy knowledge based system for target of interest differentiation with its application in matting enhancement. How to use human experience as knowledge to develop an adaptive strategy has been addressed for optimization. A recursive $\alpha$ optimization framework is used in the scheme with adaptive fuzzy learning strategy. Considering the uncertainty of data and processing, the proposed scheme successfully applies the expert human knowledge into matting. The uncertainty of data and solution are both taken into account. The measurement involved with the energy and the dimension of the anonymous pixels is introduced into the objective for optimization. The key to the success of enhancement of matting lies in the recursive learning with kernel learning and adaptive fuzzy updating strategy, enabling the solution preserve more desired details while filtering the untrustworthy information. With the consideration of the uncertainties involved with color condition, priori knowledge and solution, tail recursion and uniqueness of optimization guarantee the stability of the matting solution, enabling the proposed scheme robust to various uncertainties in matting. Experiment results are given to demonstrate the effect of the proposed method with the comparison between before and after enhanced matting. The analysis and evaluation are given as well.

*Keywords:* fuzzy knowledge system, enhanced matting, adaptive learning, recursive optimization.

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## 1. Introduction

Extracting targets of interest as foreground objects from still images or video sequences plays an important role in video editing. The foreground matting problem was mathematically established by Porter and Duff [1]. Matting refers to extracting targeted objects in visual data $I$ as foreground F from the other information as back- ground $B$. The color of each pixel $i$ in $I$ can be formulated as the combination of the colors of $F$ and $B$, that is,

$$I_i = \alpha_i F_i + (1 - \alpha_i) B_i \tag{1}$$

where $i$ presents the label of each pixel in image $I$ and $\alpha_i \in [0, 1]$ is the pixel's foreground opacity. In equation (1), $\alpha, F, B$ are unknowns, making the equation overdetermined system. For obtaining the determined solution of this equation, computer expects the user to provide priori knowledge involved with the $F$ and $B$ to constrain the system. Trimap (usually hand-drawn) is one of the techniques to provide such knowledge[2]. It segment the image into three groups, determined foreground as the target of interest with the matte $\alpha^F$, background with $\alpha^B$ and uncertain anonymous with $\alpha^A$. It segments the image into three groups of pixels: foreground pixels as the target with $\alpha^F = 1$, background pixels as not required with $\alpha^B = 0$, and anonymous pixels as uncertain with $0 < \alpha^A < 1$. Trimap is not consistent with what humans perceive from the image given as an input. In most cases, uncertain pixels in matting should be as few as possible [3]. However, it is always hard to obtain the perfect trimap. In some cases, there may be regions with little indiscernibility between foreground and background, thus rendering trimap based matting has the difficulties in handling the uncertain anonymous pixels [4].

To deal with the uncertain anonymous pixels, it is possible to use the sampling based matting (e.g.[2, 5, 6]). It estimates the uncertain $\alpha^A$ by sampling the color of the pixels in labeled regions as $F$ and $B$ in trimap with determined $\alpha^F$ or $\alpha^B$. In this case, an accurate graph model for color sampling is the key to the solution. However, due to the lack of the discipline for obtaining the perfect trimap, the stability of solution can hardly be guaranteed in most cases, thus causes the matting uncertainty. Another type of methodologies is propagation based matting (e.g.[3, 7, 8]), which updates the $\alpha$ matte by propagating the determined $\alpha^F$ and $\alpha^B$. The key to the optimal propagation lies in the interpolation strategy according to the constraint given by the labeled regions. Propagation-based methods assume that foreground and background colors are locally smooth. Mostly, the performance of these methods are reasonable in matting. However, the locally smooth assumption is not always the case in practical applications, which would render the solution of matting sub-optimal.

To categorize the anonymous pixels into target of interest or trivial background respectively is a key performance in matting. Usually, many methods have their applicabilities to different cases of local smoothness and linear characteristics in color space [4, 9, 2, 5], and the success of matting involves in the condition of imaging and the quality of the color resolution between the foreground and background. Due to the imperfect priori (trimap), there are cases inevitable to possess the anonymous pixels in the matting result since the lack of priori knowledge for matting, especially when the priori is coarse (scribbling trimap). Moreover, some imperfect imaging factors, such as focusing, exposure, acutance, chromatic aberration and camera shake, also bring about the uncertainty as the conditions for processing. Even though, there are a few techniques available for enhancing the condition of photography thus reducing the uncertainty (e.g.[10, 11, 12]), many of this type of strategies needs special equipment or extra request on imaging. Therefore, there may be the uncertainty in the solutions produced by different methods under various conditions and initial priori.

Furthermore, the uncertainty may be of different dimensions and energy scale, where the dimension part represents the range of the anonymous pixels and the energy part represents the intense. The less the dimension of the anonymous data is, the less the energy of the uncertainty is. However, partially over cutting the dimensions of the ambiguous pixels make the matting hardy, losing some useful details as mistaking them for error. On the other hand, over-relaxation of the energy minimization lead the process fail to filter the uncertainty. Therefore, it is needed a balanced matting that takes both the dimensions and the energy into account to reach the balance between, thus filtering the uncertainty while preserving the useful details.

Given those uncertainties, how to obtain a reliable optimal matting in different conditions remains as a problem. In this paper, we mainly focus on the uncertainties in matting process and propose a scheme to apply human knowledge (graphic designers experience) to reduce the uncertainties of matting. We consider both the uncertainties in the priori and the process. Besides the minimization of the energy of $\alpha$, the scale of the uncertainties is also considered as an objective for optimization.

The rest of this paper is organized as follows. Section 2 gives a preliminary introduction to the related researches. Then we formulate the problem in Section 3 and discuss the concept of balanced matting. The recursive computational framework is given in Section 4. The corresponding expert system with adaptive fuzzy learning strategy is detailed in Section 5 and the experiments and related analysis are given in Section 6. Section 7 draws a conclusion.

## 2. Preliminary

Assume there is only one optimal matting result, and then the different output can be seen as various feasible solutions with uncertain residuals. There have been many studies aiming at performing matting with consideration on minimal residuals (e.g.[6, 3, 7, 13]). However, due to the uncertainty of pixels in conditions of matting, some methods produce different results. As shown in Fig.1. the effects of different methods are uncertain in various conditions. Some methods perform more superior than others in some cases while more inferior in some other cases as seen in other works [13, 8]. The reason lies in the incomplete assumption for reaching the optimal solution. Only some suboptimal solutions can be found in the feasible solution space. Due to the lack of the commonsense knowledge, it is hard for a machine to distinguish the ambiguous information only with incomplete assumption as obtaining a complete computational assumption is also a challenge for a human to enter as input. How to bridge the gap between human and computer remains as a problem to explore.

Noticeably, in post editing, manual adjustments are used to distinguish the anonymous pixels. This implies that the experience of processing uncertainty exists in graphic arts. Once the experience can be coded in a knowledge base, it is possible to design an expert system to enable the process to distinguish the anonymous pixels automatically. Inspired by this idea, in this paper, we convert human nonlinear knowledge into logical computation to design a knowledge system for matting.

Fuzzy logic[14, 15, 16] is an efficient method to convert human knowledge into computational logic. It uses multi-valued logic with a collection of membership functions and rules to reason the truth of data. With this type of logic, a fuzzy system can perform reasoning with coded knowledge [17, 18, 19]. Many research studies have shown that fuzzy strategy serves as an efficient method to deal with uncertainty in the process. (e.g.[20, 21, 22]). Fuzzy applications in image processing (e.g.[23, 24, 25]) show the feasibility

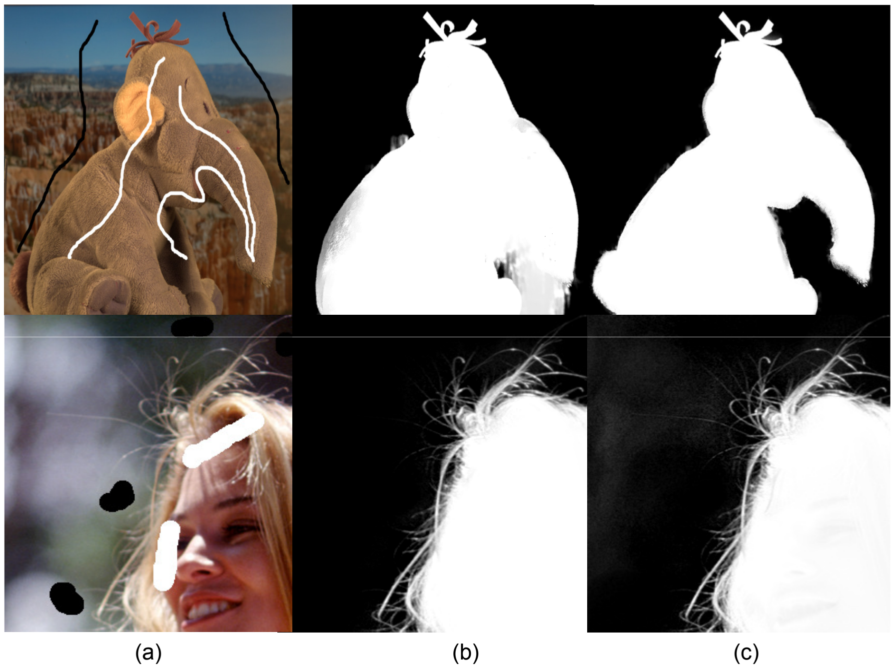



Figure 1.: An example of the uncertain output of different methods. The given cases are elephant, KNhair from the top row to the bottom respectively. As for columns, they are (a) Original $I$ with $\alpha^o$; (b) $\alpha^*$ solution by close form matting (CFM)[3]; (c) $\alpha^*$ solution by learning based matting (LBM) [7].It can be seen that the CFM perform successful matting in task KNhair but fail in task Elephant which is in contrast to the LBM.

of fuzzy systems in processing of visual data. Furthermore, with a properly adaptive strategy, fuzzy systems can update the knowledge with a dynamical learning process and deal with uncertainty under the lack of the reference priori (e.g.[26, 27]), which makes the fuzzy system advisable to use in cases that require adaptive priori acquisition. These studies imply that fuzzy systems hold the potential to process uncertain pixels in matting.

Reducing anonymous pixels can be seen as a process of filtering uncertainties in matting. Mostly, filtering takes the uncertainty as diverse noise in data. However, in matting, the image formation model is nonlinear and unknown. Much nonlinear computation is needed for the filter to distinguish the uncertain noise from the uncertain image data. Furthermore, the scenarios of matting tasks are diverse and unknown, thus hard to acquire the assumptions of the model of uncertainty. Even if the assumption of local smoothness and linear characteristics are completely held, the complexity of the nonlinearity still poses a serious challenge to the conventional filtering based methods for coping with the uncertainty in matting.

Matting is different from the de-noising process and filtering is not suitable for it, since the uncertainty of anonymous pixels cannot be taken as noise. Some fuzzy filtering strategies in image processing may not be applicable directly for the matting enhancement. Additionally, the model of the uncertainty in the solution is unknown due to the nonlinearity in image formation model. Therefore, how to design a fuzzy expert system to enhance the optimization of matting is still an issue to investigate.

To introduce the human experience into the computation, we abstract the uncertainties out from the conventional matting formulation and analyze the relationship between the optimal solution and the uncertainties. As for the human knowledge, we build a knowledge system utilizing the experience of graphic designers and convert the knowledge into computational logic by fuzzy modeling. Applying this knowledge into fuzzy expert system, we propose an adaptive learning strategy with the consideration of the uncertainties involved in the knowledge, priori and process. In the next section, let us see how problems can be formulated with the abstraction of the uncertainties.

## 3. Problem Formulation

Considering the uncertain part in the given data, let $\hat{\alpha}_i = \alpha_i + \Delta\alpha_i$ be the matte with determined $\alpha_i$ and uncertain $\Delta\alpha_i$, then the matting model (1) can be rewritten as:

$$\begin{aligned} I_i &= \hat{\alpha}_i F_i + (1-\hat{\alpha}_i) B_i \\ &= (\alpha_i + \Delta\alpha_i) F_i + (1 - \alpha_i - \Delta\alpha_i) B_i \\ &= \alpha_i F_i + (1-\alpha_i) B_i + (\Delta\alpha_i F_i - \Delta\alpha_i B_i) \\ &= \alpha_i F_i + (1-\alpha_i) B_i + \Delta\alpha_i (F_i - B_i) \\ &= \alpha_i F_i + (1-\alpha_i) B_i + \Delta\alpha_i I_i^A \end{aligned} \tag{2}$$

where $\alpha_i$ is the true $\alpha$ matte of pixel $i$; $\Delta\alpha_i$ is the unknown uncertainty of the matte; $I_i^A$ is the uncertain part of the image. Let determined foreground $\alpha$ matte $\alpha^F$ and background $\alpha^B$; $\alpha_i^A = \Delta\alpha_i$ and $\alpha^D := \{\alpha_i^D\}$; $\alpha^F := \{\alpha_i^F\}$; $\alpha_i^B = 1 - \alpha_i^F$ and $\alpha^B := \{\alpha_i^B\}$; the $\alpha$ matting model in matrix form can be formulated as:

$$I = \alpha^F \circ F^D + \alpha^B \circ B^D + \alpha^A \circ I^A = \alpha^D \circ I^D + \alpha^A \circ I^A \tag{3}$$

where '$\circ$' refers to Hadamard product, $F^D := \{F_i\}$ and $B^D := \{B_i\}$ refer to the determined foreground and background respectively, and $I^A := \{I_i^A\}$ presents the anonymous regions with uncertain matte $\alpha^B < \alpha^A < \alpha^F$, thereby $I^D, \alpha^D$ are determined information of image.

The goal of balanced matting is to minimize the anonymous $I^A$ by reducing the uncertainty of solution under the given $I, F^D, B^D$ as the knowledge for optimization.The process of reducing the anonymous pixels can be seen as the procedure to filter the uncertainties in matting. The uncertainty may be of various dimensions and energy scale, where the dimension part represents the range of the anonymous pixels and the energy part represents the intensity. The less the dimension of the anonymous data is, the less the energy of the uncertainty is. However, partially over cutting the dimensions of the ambiguous pixels make the matting hardy, losing some useful details as mistaking them for error. On the other hand, over-relaxation of the energy minimization lead the process fail to filter the uncertainty.

Considering the dimensions and the energy of the anonymous data, the energy dimension product $\omega$ is defined as (4) that

$$\omega = \dim(\alpha^A) \times \|\alpha^A\| \tag{4}$$

and, the optimization of the matting, thus, is

$$\begin{cases} \min & J(\alpha) \\ \min & \omega \\ s.t. & \alpha_i \in [0, 1] \end{cases} \tag{5}$$

where $J(\alpha)$ is the energy function of $\alpha$, and the uncertain scale of the anonymous regions $I^A$ is measured by $\omega$.

## 4. Optimal $\alpha$ Solution

The directly analytic solution of the optimal $\alpha^*$ in (5) is hard to obtain. Meanwhile, due to the uncertainty of the input, it may not be possible to assume the optimal priori. Therefore, the optimal solution is hard to obtain straightly, especially when energy product $\omega$ is considered. However, the task of the implementation is to design and implement a procedure $P$ with a method $f$ to find a series of suboptimal searching convergent to optimal solution $\alpha^*$. Given the optimal solution is satisfied with $\alpha^* = f\alpha^*$, where $f : \mathbb{R} \to \mathbb{R}$, it is possible for us to obtain the optimal solution by recursive computing. The recursive $\alpha$ learning enhanced optimization can be performed in as:

> **procedure** $P$;
> > **Data**: $\alpha^o, I$
> > **Result**: $\alpha^*$
> > **initialization**;
> > **return** $\tilde{\alpha} \leftarrow f(\tilde{\alpha}, I)$;
> > **end**

where $f$ is the recursive function with the procedure designed as:

> **procedure** $f(\alpha, I)$;
> > **initialization**;
> > $\tilde{\alpha} \leftarrow f(\alpha^o, I)$;
> > **if** $\tilde{\alpha} = f(\alpha^o, I) \bigwedge \min (5)$ **then**
> > **return** $\tilde{\alpha}$;
> > **else**
> > **return** $\tilde{\alpha} \leftarrow f(\tilde{\alpha}, I)$;
> > **end**

and $\alpha^o$ and $I$ are known as the initial solution and the original data. $\tilde{\alpha}$ represents the feasible solution, a tail recursion is applied to guarantee the learning process is well enclosed.

$$\alpha^* = P(f\alpha^o) = P(f\tilde{\alpha}) \tag{6}$$

where $f$ represents the mapping of solving the $\alpha^*$ and $\tilde{\alpha}$ refers to suboptimal solution to the (5) respectively. It can be seen in the process, suboptimal solutions $\tilde{\alpha}$ can be updated during the recursion.

To guarantee the stability of the procedure, $P$ should be terminating, or the suboptimal solution series needs to be convergent to the fixed point that When global optimal solution is obtained, the $P$ will stop at the $\alpha^*$. However, due to the uncertainty in processing and initialization, the Since the fixed point of $f$ is also a suboptimal solution within the initial pointed range, the fixed point serves as an optimal solution based on the local range.

Considering the situation above, we rewrite the recursive algorithm above in an equivalent iterative procedure as $P$ that:

$$P : \textbf{while}(\tilde{\alpha} \in \Omega) \ \textbf{do}\{\tilde{\alpha} := f\tilde{\alpha}\} \ \textbf{end} \tag{7}$$

where $\Omega \subseteq \mathbb{R}$ is the domain of the mapping defined by $f$, and we introduce the definition of terminating and non-terminating as following.

**Definition 4.1.** *Terminating: A program $P$ is terminating when $\forall x_0 \in \Omega, \exists i \in \mathbb{N}$ that $f^i(x_0) \ni \Omega$.*

**Definition 4.2.** *Non-terminating: A program $P$ is terminating when $\exists x_0 \in \Omega, \forall i \in \mathbb{N}$ that $f^i(x_0) \in \Omega$.*

When $P$ is terminating, there exists a stop point for the iterative procedure, but if not, we need to guarantee there is a fixed point of the function $f$ to make the dynamics of program $P$ stable for the system operation, especially for the procedure of searching an optimal solution iteratively.

After recursive learning, the features become increasingly clear thus extract more information about $\alpha$ out from the uncertainty. In another words, there should exist an stable point in the domain of the function $f$ or the program $P$ with $f$ should be terminating to guarantee a certainty of the procedure under uncertain circumstance, which motivates us to discuss the termination and fixed point analysis of the iterative mapping procedure.

**Lemma 1.** *Intermediate value theorem: there is a continuous function $f$ with an interval $[a, b]$, in its domain, if takes values $f(a)$ and $f(b)$ at each end of the interval, then there exists $a < c < b$ making $f(c)$ between $f(a)$ and $f(b)$ within the interval.*

**Lemma 2.** *For the program $P$ defined in (7) with a continuous mapping $f$ in domain $\Omega = (a, b)$, there exists a fixed point $\alpha^* = f(\alpha^*) \in [a, b] \subseteq \mathbb{R}$ if $P$ is non-terminating.*

*Proof:* If $P$ is Non-terminating, $\exists \alpha_0 \in \Omega, \forall i \in \mathbb{N}$ that $f^i(\alpha_0) \in \Omega$. The trajectory of the iterative path can be written as:

$$A = \{\alpha_0, f(\alpha_0), f^2(\alpha_0), f^3(\alpha_0), \ldots, f^i(\alpha_0), \ldots\}. \tag{8}$$

Let $a_{\sup} = \sup(A), a_{\inf} = \inf(A)$. If $a_{\inf} \in A$, then $f(a_{\inf}) \in A$ and $a < a_{\inf} \leq f(a_{\inf})$ because $a_{\inf}$ is the inferior bound of the trajectory $A$.

Otherwise, $\exists \{f^{kn}(\alpha_0) \subseteq A\}$, a subseries of $A$ with interval $k$, that

$$\lim_{n \to +\infty} f^{kn}(\alpha_0) = a_{\inf} \tag{9}$$

in which $a \leq a_{\inf}$. Due to the continuation of the mapping $f$, we have $\lim_{n \to +\infty} f(f^{kn}(\alpha_0)) = f(a_{\inf})$.

Because $a_{\inf}$ is the inferior bound of $A$, we have $a_{\inf} < f(f^{kn}(\alpha_0))$ thus, yielding $a_{\inf} \leq f(f^{kn}(\alpha_0))$. Therefore, we have $a \leq a_{\inf} \leq f(f^{kn}(\alpha_0))$.

Similarly, we can prove $f(f^{kn}(\alpha_0)) \leq a_{\sup} \leq b$.

If $a_{\inf} = f(a_{\inf})$ or $a_{\sup} = f(a_{\sup})$, then $a_{\inf}$ or $a_{\sup}$ is the fixed point. Otherwise, let $g(\alpha) = f(\alpha) - \alpha, \alpha \in [a_{\inf}, a_{\sup}]$. Because $g(\alpha)$ is a continuous function in $[a_{\inf}, a_{\sup}]$, and $g(a_{\inf}) > 0, g(a_{\inf}) < 0$, by *Lemma* 1, we have $\exists \alpha^* \in [a_{\inf}, a_{\sup}] \subseteq [a, b]$ that $g(\alpha^*) = 0$, i.e., $\alpha^*$ is the fixed point for $\alpha^* = f(\alpha^*)$. Thus, the statement has been proven. □

**Theorem 1.** *There exist $a$ and $b$ as the terminal points of the domain $\Omega \subset \mathbb{R}$, with a function $f$ satisfying $f(a) \neq a$ and $f(b) \neq b$. The program $P$ defined in* (7) *with $f$ in domain $\Omega$ is non-terminating if and only if there exists a fixed point $\alpha^* = f(\alpha^*) \in (a, b) \subseteq \mathbb{R}$.*

*Proof:* For the sufficiency, it can be proven by *Lemma* 2. For the necessity, if there exists a fixed point $\alpha^* = f(\alpha^*) \in [a, b] \subseteq \mathbb{R}$, then the program $P$ will always meet *Definition* 4.2, which means that it is non-terminating. Thus, the statement has been proven. □

**Corollary 1.** *For the program $P$ defined in* (7) *with a continuous mapping $f$ in domain $\Omega = (-\infty, +\infty)$, there exists a fixed point $\alpha^* = f(\alpha^*) \in \Omega$ if and only if $P$ is non-terminating.*

*Proof:* When $-\infty, +\infty$ are included in the $\Omega$, the terminal points are fixed points, and $\infty$ cannot be practically used as initial solution for the program $P$. Therefore, the substitution $a = -\infty$ and $b = +\infty$ are available for *Theorem* 1 and the statement can be justified by similar the way of proving *Theorem* 1. □

**Corollary 2.** *For the program $P$ defined in* (7) *with a continuous mapping $f$ in domain $[a, b] \subset \Omega \subseteq \mathbb{R}_\infty$ that $\mathbb{R}_\infty = \mathbb{R} \cup -\infty, +\infty$, there exists a fixed point $\alpha^* = f(\alpha^*) \in [a, b]$ if and only if $P$ is non-terminating.*

We design the process as learning that takes $F^D, B^D, I$ as state of system and $\alpha^A, \alpha^F, \alpha^B, I^A$ as knowledge of matting. The learning process includes three phases: state estimation, self-learning, and knowledge update.

The state estimation phase can be modeled as:

$$\begin{cases} F^D = f_1(\alpha^F, I) \\ B^D = f_2(\alpha^B, I) \end{cases} \tag{10}$$

where $f_1, f_2$ are estimation mappings for learning based on the existed priori, and the update as:

$$\begin{cases} \alpha = f_3(\alpha^F, \alpha^B, F^D, B^D, I) \\ \alpha^A = f_4(\alpha, \alpha^F, \alpha^B) \\ \alpha^D = f_5(\alpha, \alpha^F, \alpha^B) \end{cases} \tag{11}$$

where $f_3$ is the learning mapping, $f_4, f_5$ are update mappings to obtain the suboptimal solution.

The estimation mappings in (10) are designed as $f_1 = f_2 = f_e$ where

$$f_e(\alpha, I) = \alpha \times I \tag{12}$$

It can be seen that $f_e$ is injective, and $I$ is a constant, therefore $f_e$ provides robust $\alpha$ solution.

The learning functions $f_3 = f_l$ is designed as (6). Considering the residual comes from anonymous pixels, we formulate the recursive model (6) with optimization (5) as

$$\alpha = \arg\min_{\alpha, I} J(\alpha) + \omega \tag{13}$$

To simplify, we introduce a relaxation factor $\gamma$. combining with (6), (13) can be rewritten as:

$$\alpha = \arg\min_{\alpha, I} (\|\alpha - f\alpha\| + \gamma\|\alpha^A\|) \tag{14}$$

where the first norm refers to the energy of the global uncertainty in the data, and the latter one refers to the energy of uncertainty in local anonymous regions.

## 5. Adaptive Fuzzy Learning

### *5.1. The Knowledge Modeling*

Considering the uncertainty in both the solution and the processing, we model the uncertain matting as a fuzzy set. Given the uncertainty in the solution $\alpha$, we taken the uncertain solution as $\tilde{\alpha}$.

The knowledge system for distinguishing the attribution of the solutions is modeled as:

$$\begin{array}{ll} \textbf{IF}: & \tilde{\alpha}^1 \text{is} X_1, \tilde{\alpha}^2 \text{is} X_2, \cdots, \tilde{\alpha}^k \text{is} X_k, \cdots, \tilde{\alpha}^N \text{is} X_N, \\ \textbf{THEN}: & \hat{\alpha} \text{ is } Y; \\ \textbf{STATES}: & X \in \{\text{RB,DB,RF,DF,RA,DA}\} \text{ and} \\ & Y \in \{\text{UB,BT,UF,FT}\} \end{array} \tag{15}$$

where $\hat{\alpha}$ is the estimated $\alpha$ from the input uncertain elements $\tilde{\alpha}^k, (k = 1, 2, \ldots, N)$. $X_k, (k = 1, 2, \ldots, N)$ and $Y$ are the state of the uncertain and estimated $\alpha$.

As for the state domains, RB refers to resembling background that the value is close to the referred background $\alpha$ value, DB refers to dissimilar background that the value is far away from the referred background $\alpha$ value, RF refers to resembling foreground, DF refers to resembling foreground, RA refers to resembling anonymous, DF refers to resembling anonymous, UB refers to uncertain background, BT refers to background tending, UF refers to uncertain foreground, FT refers to foreground tending. To simplify the knowledge base, only three main uncertain elements of uncertain $\alpha$ solution are taken into consideration, they are $\tilde{\alpha}^k, (k = F, B, A)$, where $\tilde{\alpha}^F$ refers to the foreground element, $\tilde{\alpha}^B$ refers to the background, and $\tilde{\alpha}^A$ refers to anonymous element. The corresponding knowledge rule can be represented as table 1.

Table 1: The Knowledge System of $\alpha$ Judgment

| | State | | | | | |
|---|---|---|---|---|---|---|
| $\tilde{\alpha}^B$ | RB | RB | DB | DB | DB | DB |
| $\tilde{\alpha}^F$ | DF | DF | RF | RF | DF | DF |
| $\tilde{\alpha}^A$ | RA | DA | RA | DA | RA | DA |
| $\hat{\alpha}$ | UB | BT | UF | FT | UB/UF | UB/UF |

### *5.2. The Fuzzy System*

Based on the knowledge system given above, we introduce the membership degree $\mu_i$ for each $\tilde{\alpha}_i$ as a ambiguity measurement.

$$\mu_i = \frac{1}{1 + d(\tilde{\alpha}_i, \alpha^r)} \tag{16}$$

where $d(x, y)$ represents the distance measurement between $x, y$ and $\alpha^r$ refers to the reference value of the solution. Thus the solution with uncertainty can be modeled as a fuzzy set $A$ as:

$$A = \left[ \frac{\mu_1}{\tilde{\alpha}_1}, \frac{\mu_2}{\tilde{\alpha}_2}, \ldots, \frac{\mu_i}{\tilde{\alpha}_i}, \ldots \frac{\mu_n}{\tilde{\alpha}_n} \right] \tag{17}$$

where $\mu_i$ is the membership function associated with the value $\tilde{\alpha}_i$.

To assess the of the possibly optimal matting, the priori of the uncertainty is needed to estimate $\tilde{\alpha}$. Considering the similarity between each pixel and its neighbors, the neighborhood is adopted for self learning that the learning of each pixel $i$ takes place in the neighbor area of $i$ that $\Omega_i$. Assuming the intensity of each pixel $i$ in data $I$ is $x_i$, the self kernel of data pixel $i$ is

$$\Phi_i = [\{\phi(x_i, x_j)\}_{ij}], \forall i, j \in \Omega_i \tag{18}$$

which is a matrix function consists of the elements of sub-kernel $\phi(x_i, x_j)$ of each pixel $i$. In this paper,nonsingular kernel is adopted to improve the kernel feature for solution that

$$\phi(x_i, x_j) = \begin{cases} [C(X)_{i,j}]^{-1} exp\|x_i - x_j\| & i \neq j \\ \epsilon & i = j \end{cases} \tag{19}$$

where $C(X)_{i,j}$ is the covariance of the $i$th $j$th pixels in intensity $X$, and $\epsilon > 0$ is the nonsingular factor.

Correspondingly, the kernel vector of the pixel $i$ can be written as:

$$k_i = [\phi(x_i, x_1), \phi(x_i, x_2), \ldots, \phi(x_i, x_i), \ldots, \phi(x_i, x_n)]^T \tag{20}$$

The kernel features $k$ of each pixel $i$ can be represented by the self $F_i$ feature that $\Phi_i F_i = \beta k_i$, and thus

$$f\tilde{\alpha} = [\Phi_1^{-1}\beta k_1, \Phi_2^{-1}\beta k_2, \ldots, \Phi_N^{-1}\beta k_N]\tilde{\alpha} = \Psi\beta k\tilde{\alpha} \tag{21}$$

and the mapping $\gamma$ can be extended as linear form as

$$\Gamma = \mathrm{diag}(\gamma_1, \gamma_2, \ldots, \gamma_n) \tag{22}$$

where

$$\gamma_i = \begin{cases} \gamma & \sup\{\alpha^B\} < \tilde{\alpha}_i < \inf\{\alpha^F\} \\ 0 & else \end{cases} \tag{23}$$

Thus (14) can be rewritten as:

$$\tilde{\alpha} = \arg\min_{\alpha, I} \alpha^T G G^T \alpha + (\alpha^A)^T \Gamma (\alpha^A) \tag{24}$$

where

$$G = I - \Psi\beta k \tag{25}$$

According to (5), we have $\|\alpha^A\| = \|\alpha - \alpha^D\|$, and the solution in close form of (24) can be obtain by semi-transductive learning[28, 29], as:

$$\tilde{\alpha} = (GG^T + \Gamma)^{-1}\Gamma\alpha^D = R\alpha^D \tag{26}$$

which makes $f_3$.

Let the uncertainty in the solution $\alpha$ as $\delta$, then the uncertain solution can be represented as $\alpha_i \pm \delta$. Correspondingly, the obtained uncertain solution $\tilde{\alpha}_i$ can be modeled as:

$$\tilde{\alpha}_i = \frac{\tilde{\alpha}_i^F + \tilde{\alpha}_i^B}{2} \tag{27}$$

where

$$\begin{cases} \tilde{\alpha}_i^F = \tilde{\alpha}_i + \delta \\ \tilde{\alpha}_i^B = \tilde{\alpha}_i - \delta \end{cases} \tag{28}$$

where $\tilde{\alpha}_i^F, \tilde{\alpha}_i^B$ are the estimations of foreground and background matte with uncertainty $\delta$ respectively. Using the estimations as the obtained $\tilde{\alpha}_i^F$, and considering the uncertainties, we have:

$$A^F = \left[\frac{\mu_1^F}{\tilde{\alpha}_1^F}, \frac{\mu_2^F}{\tilde{\alpha}_2^F}, \ldots, \frac{\mu_i^F}{\tilde{\alpha}_i^F}, \ldots \frac{\mu_m^F}{\tilde{\alpha}_m^F}\right] \tag{29}$$

where $m$ is the number of the $F$ matte, and the corresponding member functions $\mu_i^F$ are

$$\mu_i^F = \frac{1}{1 + d(\tilde{\alpha}_i^F, \inf \alpha^F)} \tag{30}$$

Similarly, $A^B$ and $\mu^B$ can be obtained with the same procedure.

### *5.3. The Adaptive Learning*

Considering the a quadratic cost function that

$$J(\bar{\alpha}) = (\tilde{\alpha} - \bar{\alpha})^T f(\mu)(\tilde{\alpha} - \bar{\alpha}) \tag{31}$$

where $\bar{\alpha}$ refers to the mean of the reference value of $\alpha^r$. When $J(\bar{\alpha})$ reaches to its minimum, the optimal solution is obtained as:

$$\hat{\alpha} = \arg\min J(\bar{\alpha}) = \frac{\sum_k f(\mu^k)\tilde{\alpha}^k}{\sum_k f(\mu^k)} \tag{32}$$

Given the changing of the uncertainty and anonymous information during the recursive learning, we further design adaptive strategy for dynamical estimation of optimal solution. The membership function of the anonymous uncertainty is defined as:

$$\mu_i^A = \begin{cases} \frac{1}{\bar{\alpha}^A} & \tilde{\alpha}_i \leq \bar{\alpha}^A \\ \frac{\tilde{\alpha}_i - 1}{\bar{\alpha}^A - 1} & \bar{\alpha}^A < \tilde{\alpha}_i \leq 1 \end{cases} \tag{33}$$

where $\bar{\alpha}^A$ is the mean of the anonymous $\alpha^A$. Therefore, with the process of the recursive learning, the parameter will be adjusted according to the dynamics of anonymous $\alpha^A$. The fuzzy learning strategy is adaptive to the uncertain measurement as:

$$\begin{cases} f(\mu_i^F) = \mu_i^F + \lambda sgn(\tilde{\alpha}_i - \bar{\alpha})\mu_i^A \\ f(\mu_i^B) = \mu_i^B - \lambda sgn(\tilde{\alpha}_i - \bar{\alpha})\mu_i^A \end{cases} \tag{34}$$

where $\lambda$ is a coefficient for adaptive rate. Substituting (34) into (35), it yields

$$\hat{\alpha}_i = \frac{f(\mu_i^F)\tilde{\alpha}_i^F + f(\mu_i^B)\tilde{\alpha}_i^B}{f(\mu_i^F) + f(\mu_i^B)} \tag{35}$$

Thus, we obtain the defuzzed estimation by fuzzy learning according to the knowledge system.

Using the (30) to mapping the $\hat{\alpha}$ into fuzzy set, $\mu^F, \mu^B$ of estimated solution can obtained to update the priori, where $\alpha^F, \alpha^B$ are obtained by cut set that:

$$\begin{cases} \alpha^F = A^F_{\inf \mu^F} = \{\hat{\alpha}_i | \mu_i^F \geq \sup \mu^F\} \\ \alpha^B = A^B_{\inf \mu^B} = \{\hat{\alpha}_i | \mu_i^B \leq \inf \mu^B\} \end{cases} \tag{36}$$

Then, the mapping for update $f_5$ in (11) is designed as:

$$f_5(\alpha^F, \alpha^B) = \alpha^F + \alpha^B \tag{37}$$

meanwhile

$$\alpha^A = \alpha - \alpha^D \tag{38}$$

that makes the $f_4$. Let $\otimes$ be the Kronecher mapping product that $[f_1, f_2]^T \otimes [x, y] = [f_1(x, y), f_2(x, y)]^T$, then (10),(11) can be modeled in compact formulation as:

$$x = f \otimes x \tag{39}$$

where

$$\begin{cases} x = [\alpha^F, \alpha^B, F^D, B^D, I] \\ f = [f_1, f_2, f_3, f_4, f_5]^T \end{cases} \tag{40}$$

### *5.4. Discussion*

Combining fuzzy learning and adaptive strategy, the equation (39) performs an adaptive fuzzy learning enhance optimization (AFLEO) for matting in a form of recursive learning procedure $P$, it can be seen that $f_1, f_2, f_3, f_4, f_5$ are continuous function in the domain $[0, 1]$. Thus, with *Theorem* 1 and *Corollary* 2, we may have following conclusion.

**Proposition 1.** *With given $\alpha^o$ and $I$, an optimal solution $\alpha^* \in x$ can be found with AFLEO procedure $P$ with mapping $f \otimes x$ at the fixed point of $f$ if and only if $P$ is non-terminating.*

## 6. Experiment

In this section, we present qualitative and quantitative analysis of results of testing the proposed algorithm. The test results show the performance of learning enhanced optimization with adaptive fuzzy strategy for enhancing matting. To test the performance in processing the uncertainty, scribble-map approach has been adopted as the case in matting. There are three tests in the testing to show the comprehensive performance.

### *6.1. Qualitative Analysis*

Cases for the first test are to test the basic matting performance. As shown in Fig.2., case Kid1, Kid2 and Teddy are selected and the results obtained by proposed adaptive fuzzy learning enhanced optimization (AFLEO) are given. To show the characteristics of the different methods, by comparing with the results obtained by closed-form matting (CFM) [3] and learning based matting (LBM) [7], it can be seen that all three methods are successful in performing the matting but still some subtle differences exist among those. The optimal solution obtained by CFM tends to be adamant that with less intermediate value while LBM provide more interim values. Adamant solution excludes much noise to make the matting clearer while losing some details. In contrast, intermediate values are helpful for preserving the details but may harbor some uncertain limbo. With knowledge base and expert system, AFLEO can distinguish more desired details while filtering the noise, achieving more balanced matting. Generally, the methods are acceptable in terms of the quality of matting results.

In order to show the stability of the matting performance, cases for the second test are chosen with the consideration of both the color condition and

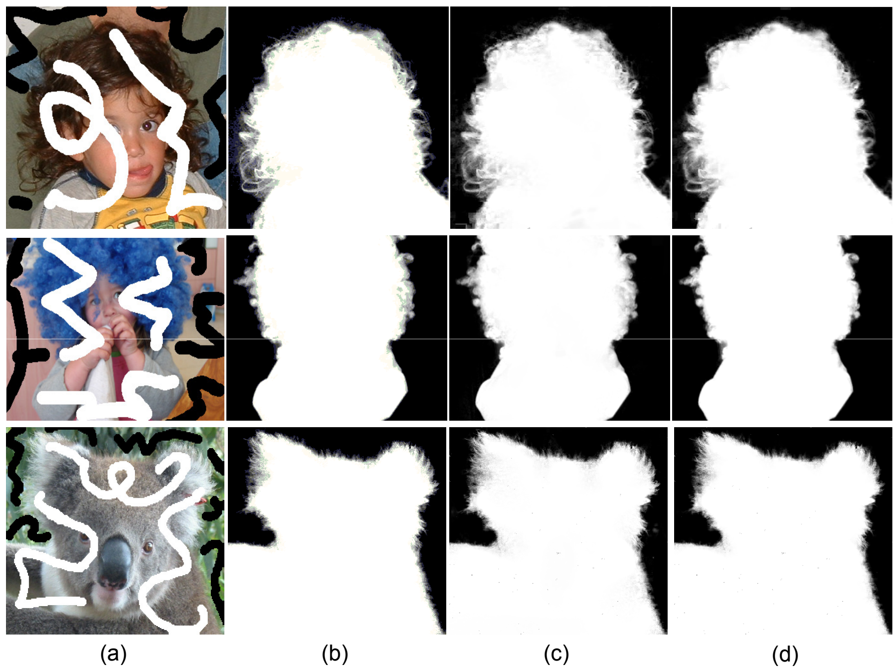



Figure 2.: The given cases are Kid1, Kid2 and Teddy from the top row to the bottom respectively. As for columns, they are (a) Original $I$ with $\alpha^o$ and the $\alpha^*$ solution by CFM[3] (b), LBM [7](c) and by AFLEO(d).

scribble map, where the case elephant is characterized ambiguous color condition with medium intended scribbling map, the KNhair is less ambiguous but more complicated color with sparse intended scribbling map, and the donkey has ambiguous color with much casual scribbling map.

As shown in Fig.3., results show the applicability of different methods for various cases. In case elephant (the first row in Fig.3.), LBM performs well in matting while CFM fails to matte the scene since. However, in case KNhair (the second row in Fig.3.), LBM fails to obtain a clear matting since the color line assumption is invalid while CFM perform satisfactory result even though the color is complicated. In the case donkey, both CFM and LBM perform inferior matting, in which CFM gives a hardy matting that loses lots of information of the target and LBM fails to provide a clear matting although it preserves more details of the foreground. With the adaptive learning algorithm and the guarantee of the stability, AFLEO handles uncertain pixels

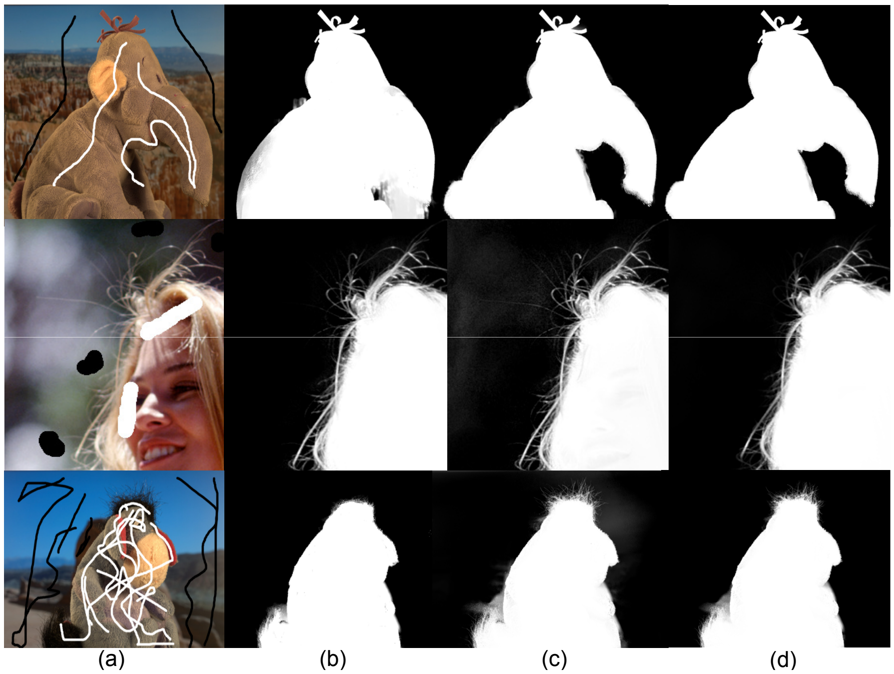
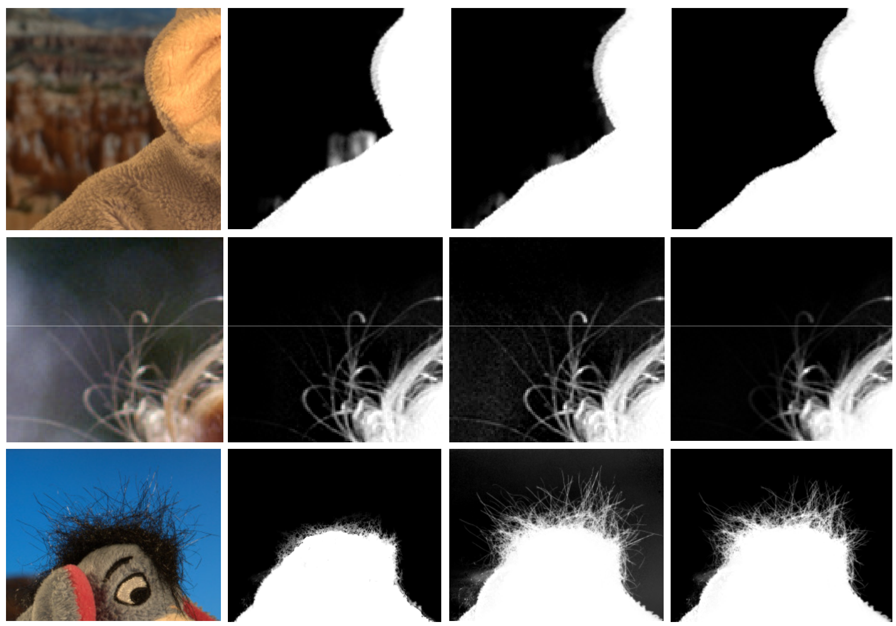



Figure 3.: The given cases, elephant, KNhair and donkey, are given with scribbling maps as column (a) from the top row to the bottom respectively. From (b)-(d) are $\alpha^*$ solution by CFM[3], LBM[7] and AFLEO respectively.

and perform stable matting. Fig.4. gives a close look at the results. It shows that, besides to obtain the optimal solution, AFLEO is capable of providing a balance matting with the guarantee of the robustness.

Considering the usability differences in users [30, 31], we have tested the usable reliability of the processing in the third tests. Case Gandalf is used as the object for testing. Given the diversity of the experience of the various users, we ask three type of users with the different levels of expertise in photo edition, to provide the priori for the matting. The first user is a professional graphic designer, the second an amateur photographer, and the third a layman. As shown in Fig.5., the graphic designer has provided an outline style (OS) scribbling map as the priori, and the amateur photographer freestyle but sparse priori (FS). The third user has given a lineation style (LS) priori. It can be seen that AFLEO can provide a reliable usability to the differences in the type of users with a robust performance. This implies that



(a) (b) (c) (d)

Figure 4.: The comparison in local details in the matting of elephant, KNhair and donkey. As for columns, they are (a) Original $I$; (b) $\alpha^*$ solution by CFM[3]; (c) $\alpha^*$ solution by LBM [7]; (d) $\alpha^*$ solution by AFLEO;

AFLEO can guarantee a stable user experience.

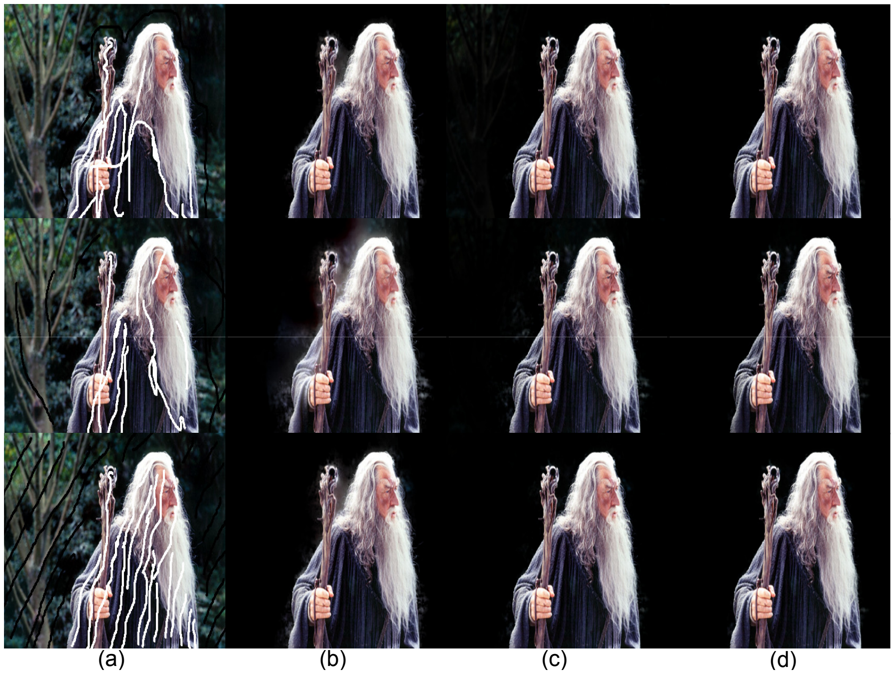


Figure 5.: As in column (a) from the top row to the bottom, it is the case Gandalf with outline style, freestyle and lineation style priori. From (b)-(d) are the matting results by close form matting (CFM)[3], learning based matting (LBM) [7] and AFLEO respectively.

### *6.2. Quantitative Analysis*

To give a further quantitative evaluation, the performance of the results is counted in terms of $\dim(\alpha^A)$ and $\|\alpha^A\|$. We define the macro energy dimension product (MEDP) $\bar{\omega}$ as

$$\bar{\omega} = (E(\dim(\alpha^A)) \times E(\|\alpha^A\|)) \tag{41}$$

to measure the uncertainty caused by anonymous pixels regarding all the tests, where $E(\dim(\alpha^A))$ and $E(\|\alpha^A\|)$ are expectations (expected value) for the methods. To scale the calculation, log function is used to show the results clearly in a downsize way as $\log(\bar{\omega})$. As shown in table 2, the performance of each method is counted in terms of $\dim(\alpha^A)$, $\|\alpha^A\|$ and $\omega$. It also can

Table 2: The Statistics of Evaluation Based on $\dim(\alpha^A)$ and $\|\alpha^A\|$

| | CFM[3] | | LB[7] | | AFLEO | |
|---|---|---|---|---|---|---|
| | $\dim(\alpha^A)$ | $\|\alpha^A\|$ | $\dim(\alpha^A$ | $\|\alpha^A\|$ | $\dim(\alpha^A)$ | $\|\alpha^A\|$ |
| Kid1 | 15100 | 37.50 | 15100 | 37.91 | 12358 | 34.00 |
| Kid2 | 5571 | 29.84 | 5569 | 29.84 | 3991 | 19.29 |
| Teddy | 16553 | 40.96 | 16912 | 40.95 | 14957 | 37.03 |
| Elephant | 55293 | 45.45 | 13020 | 21.98 | 8232 | 18.34 |
| Hair | 8657 | 22.98 | 14431 | 24.13 | 7544 | 20.74 |
| Donkey | 30414 | 28.40 | 47096 | 44.94 | 17135 | 35.10 |
| Gandalf OS | 4933 | 16.99 | 12587 | 17.70 | 4642 | 16.97 |
| Gandalf FS | 20925 | 43.19 | 15138 | 36.80 | 10459 | 42.10 |
| Gandalf LS | 7467 | 23.04 | 7111 | 23.15 | 5329 | 20.70 |
| Average | 25757 | 31.93 | 16329 | 30.82 | 9405 | 27.14 |
| $\log \bar{\omega}$ | 13.6200 | | 13.1289 | | 12.4500 | |

be seen that the $\dim(\alpha^A)$ and $\|\alpha^A\|$ are maintained in reasonable value by AFLEO, and the dimension of anonymous data is matched with its energy. It implies that AFLEO recognize the more desired anonymous pixels as determined information while performs robust suitability for cases with different conditions of color and scribbling map.

To have a close look at the robustness and stability of each method in detail, the logarithm of $\omega$ of each test each method has been shown in Table 3. The expectation of the logarithm energy dimension product (ELEDP) is introduced to assess the comprehensive performance in micro analysis view, obtained by:

$$(E(\log \omega)) = E(\log(\dim(\alpha^A) \times \|\alpha^A\|)) \tag{42}$$

Comparison criterion of EDP $\Delta_{EDP}$ is introduced to evaluate the stability performance of the matting methods regarding the macro and micro evaluations. $\hat{\omega}$ is obtained by (43),

$$\Delta_{EDP} = E(\log \omega)) - \log E(\omega)) \tag{43}$$

The results are shown in Table 3.

As shown in Table 3, the index of AFLEO is optimal (12.27) among the three schemes. Besides the optimal solution overall, the $\omega$ of AFLEO in each test is also optimal, which implies it is able to provide a balance matting

Table 3: The Statistics of Evaluation Based on EDP $\omega$

| $\log(\omega)$ | Kid1 | Kid2 | Tedd. | Elep. | Hair | Donk. | G.OS | G.FS | G.LS | ELEDP | $\Delta_{EDP}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CFM[3] | 13.25 | 12.02 | 13.43 | 14.74 | 12.20 | 13.67 | 11.34 | 13.71 | 12.06 | 12.93 | 0.69 |
| LB[7] | 13.28 | 12.02 | 13.45 | 12.56 | 12.76 | 14.57 | 12.31 | 13.23 | 12.01 | 12.91 | 0.21 |
| AFLEO | 12.95 | 11.25 | 13.22 | 11.92 | 11.96 | 13.31 | 11.27 | 13.00 | 11.61 | 12.27 | 0.18 |

with the robustness against different cases. Among the tests, the $\dim(\alpha^A)$ and $\|\alpha^A\|$ are maintained in reasonable value by AFLEO, and the energy of uncertainty is kept matching with its scale in anonymous dimension. As for the $\Delta_{EDP}$, it can be seen that AFLEO has the minimal residual (0.18) compared with the scheme both CFM (0.69) and LBM (0.21). means that under same given conditions, AFLEO tends to be more robust to the various uncertain situation, thus guaranteeing the reliable optimization for enhanced matting.

To give a further quantitative illustration, the statistics of the tests are given in Fig.6.-14., as the distribution of the matting results in the tests Kid1, Kid2, Teddy, Elephant, KNHair, Donkey, Gandalf with OS, FS, and LS, obtained by CFM, LBM, AFLEO respectively. The vertical axis represents probability and the horizontal axis represents the alpha value. As shown in Fig.6.-14., under different situations, the performance of the results of AFLEO tends to close to the optimal solution. This is because the AFLEO can recognize the useful details from the ambiguous uncertainties recursively with the help of the knowledge. Using the adaptive learning algorithm, the information of foreground and background is enhanced while filtering the noise. The analysis above implies that more energy in ambiguous uncertainties is converted into determined information for the differentiation of desired details reconstruction thus enabling AFLEO to perform reasonably better for the cases with different conditions of color and scribbling map.

## 7. Conclusion

In this paper, we have proposed an adaptive learning strategy for enhanced matting with the consideration of uncertainty. A recursive $\alpha$ learning scheme is designed with the guarantee of the stability for the optimal solution. The number and the energy of the anonymous pixels are also considered

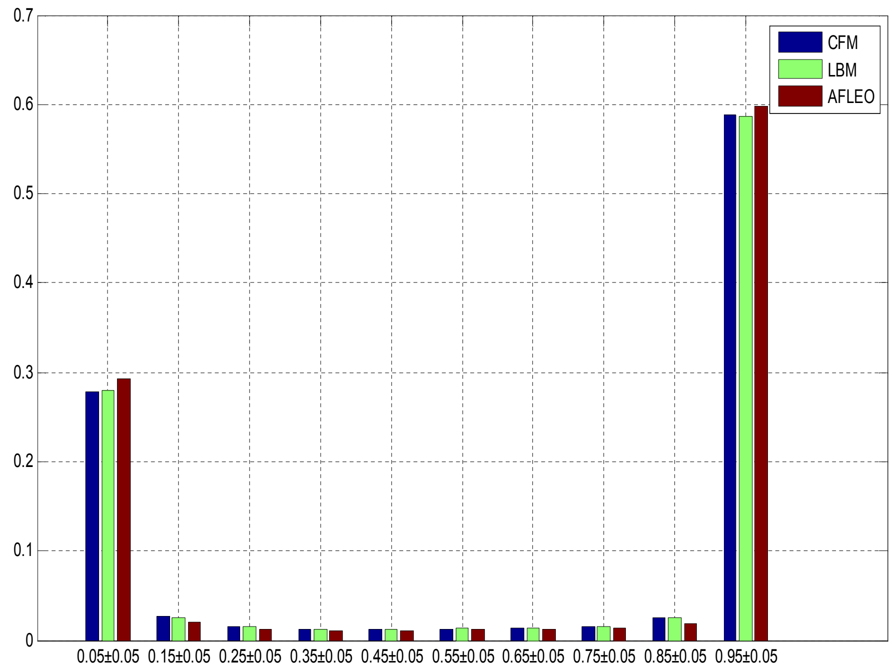



Figure 6.: The distribution of the matting results in the tests Kid1 obtained by CFM, LBM ,AFLEO respectively. The vertical axis represents probability and the horizontal axis represents the alpha value.

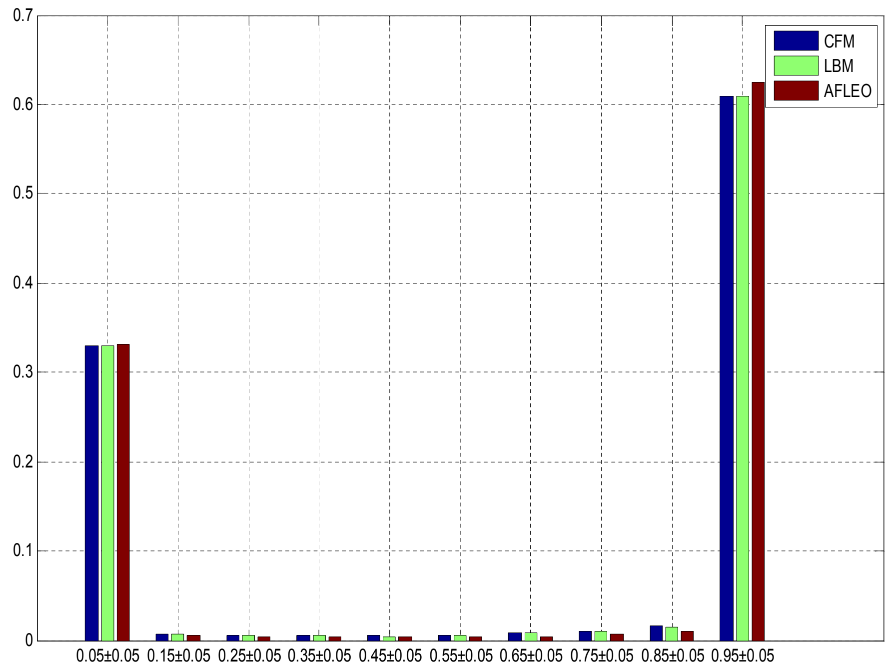



Figure 7.: The distribution of the matting results in the tests Kid2 obtained by CFM, LBM ,AFLEO respectively. The vertical axis represents probability and the horizontal axis represents the alpha value.

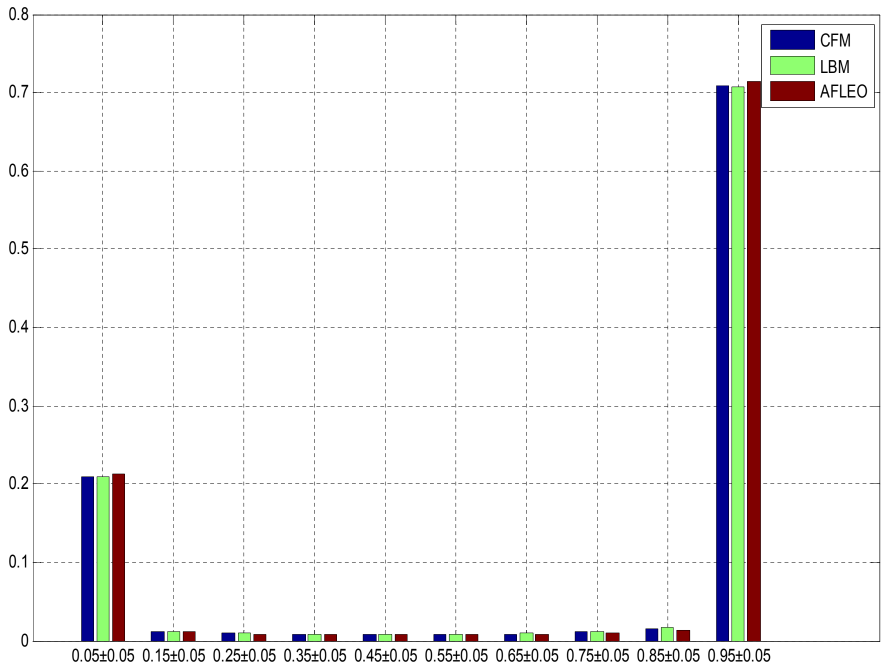



Figure 8.: The distribution of the matting results in the tests Teddy obtained by CFM, LBM ,AFLEO respectively. The vertical axis represents probability and the horizontal axis represents the alpha value.

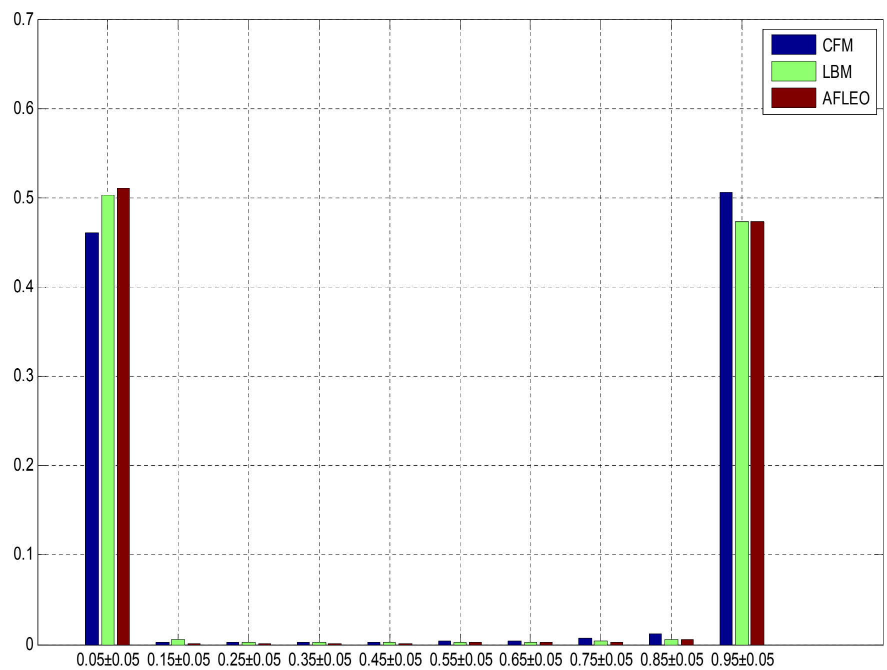



Figure 9.: The distribution of the matting results in the tests Elephant obtained by CFM, LBM ,AFLEO respectively. The vertical axis represents probability and the horizontal axis represents the alpha value.

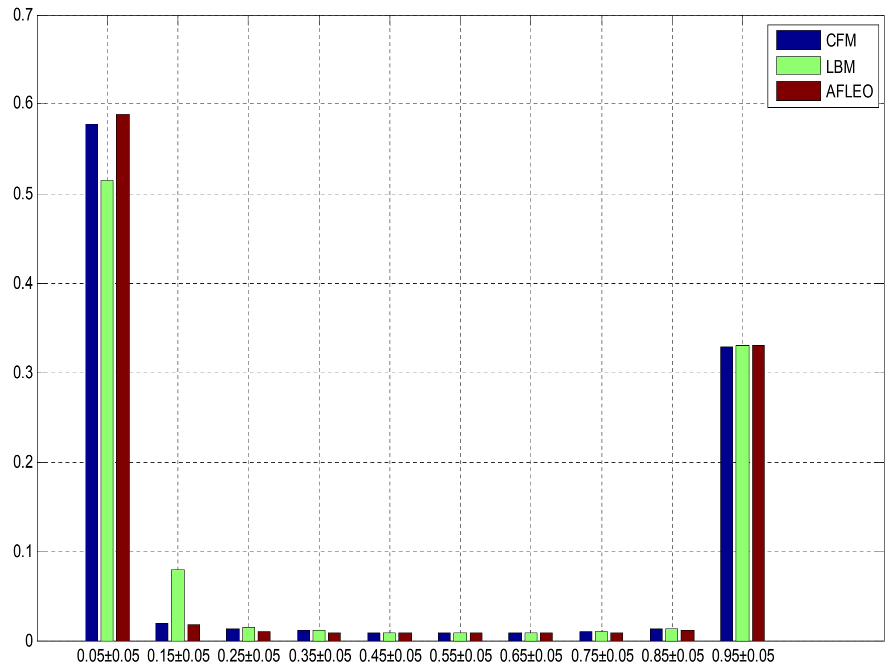



Figure 10.: The distribution of the matting results in the tests KNHair obtained by CFM, LBM ,AFLEO respectively. The vertical axis represents probability and the horizontal axis represents the alpha value.

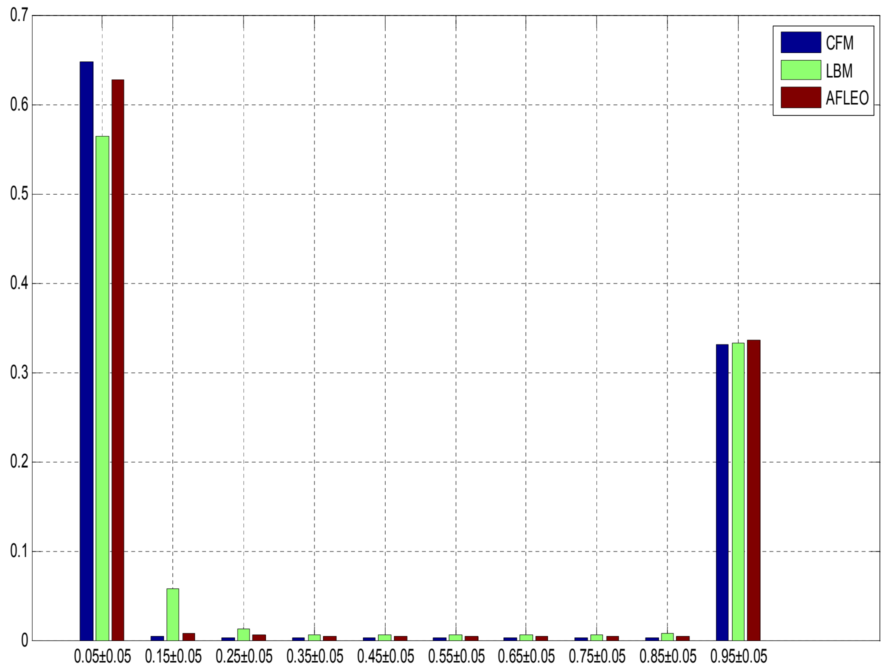



Figure 11.: The distribution of the matting results in the tests Donkey obtained by CFM, LBM ,AFLEO respectively. The vertical axis represents probability and the horizontal axis represents the alpha value.

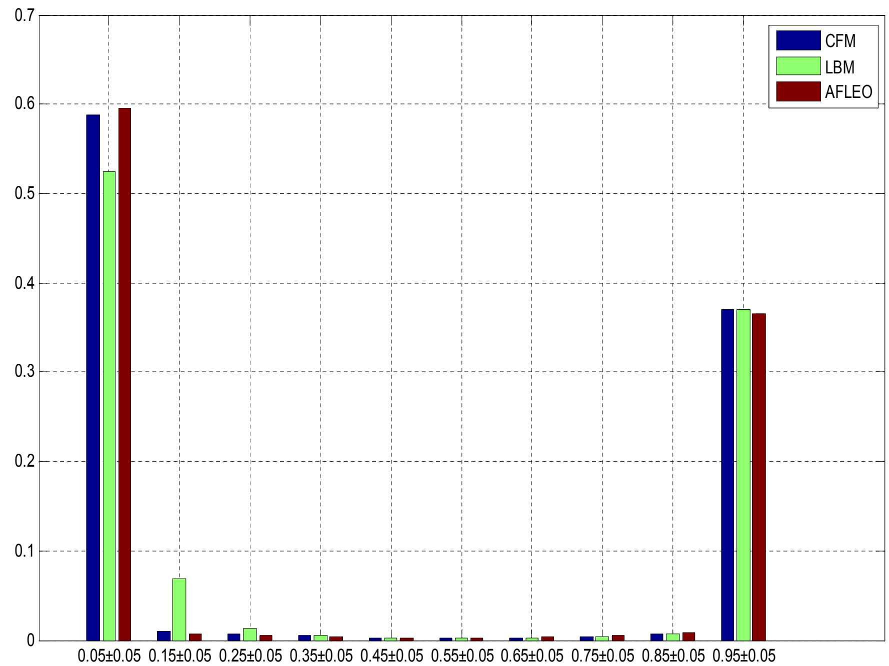



Figure 12.: The distribution of the matting results in the tests GandalfOS obtained by CFM, LBM ,AFLEO respectively. The vertical axis represents probability and the horizontal axis represents the alpha value.

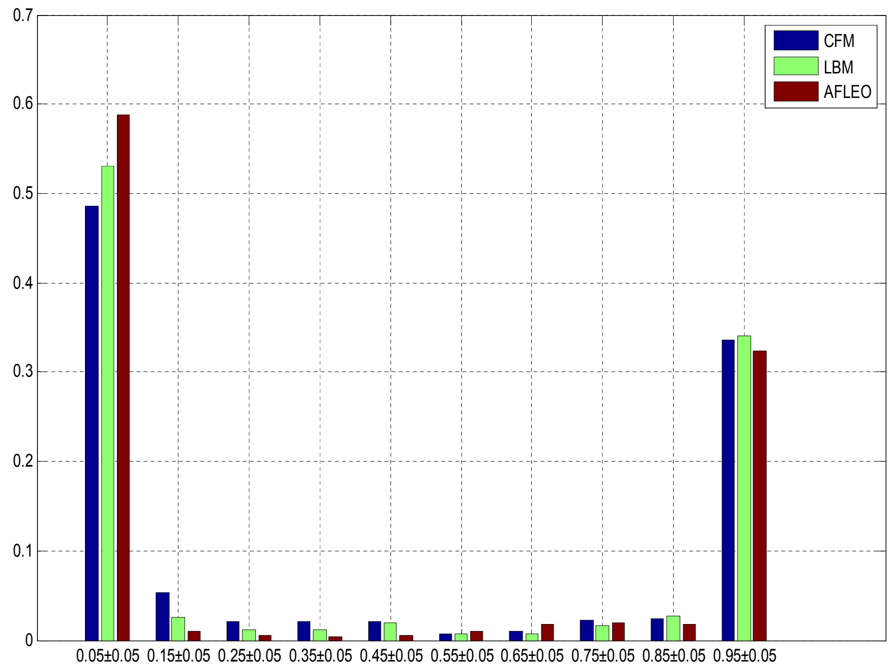



Figure 13.: The distribution of the matting results in the tests GandalfFS obtained by CFM, LBM ,AFLEO respectively. The vertical axis represents probability and the horizontal axis represents the alpha value.

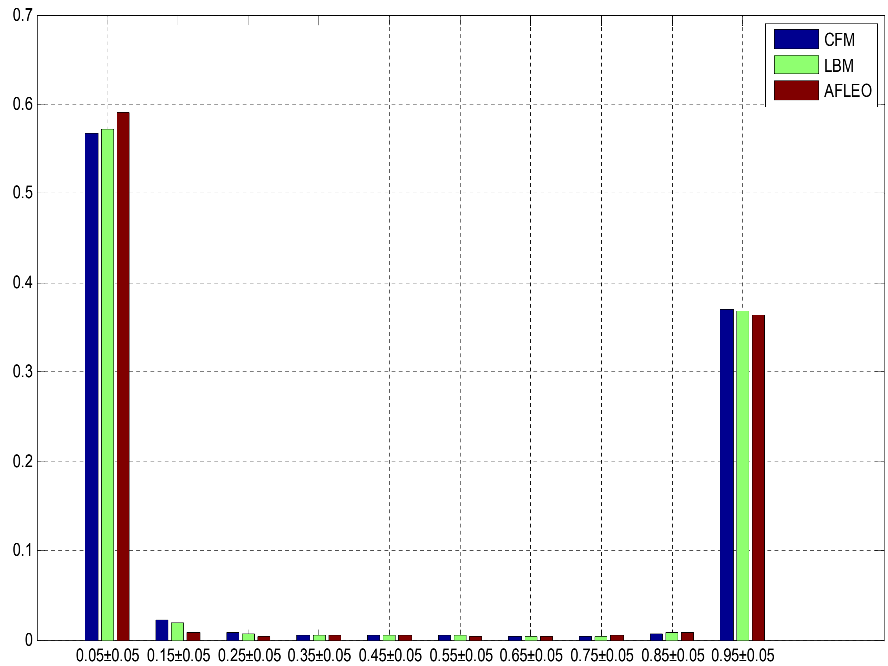



Figure 14.: The distribution of the matting results in the tests GandalfLS obtained by CFM, LBM ,AFLEO respectively. The vertical axis represents probability and the horizontal axis represents the alpha value.

as an objective for optimization to reduce the uncertainty of matting. Combining with kernel-learning and recursive update process, a balance matting can be performed The experimental results suggest that the proposed strategy can perform a balance matting that that preserves desired level of details while filtering the untrustworthy information. The robust properties of the learning operator guarantees the stability of the solution, thus enabling proposed algorithm robust to differences in the smoothness features and priori assumptions. A quantitative evaluation is also presented to demonstrate the efficiency of the proposed algorithm.

Knowledge systems with fuzzy reasoning strategy is used to model the uncertainty both in the solution and the process, and enhance the reliability of the solutions by the evaluating the membership degree based on the knowledge. Considering the dynamical changing in anonymous information during the learning, adaptive learning strategy is used as well. Proposed scheme only set the learning rate for system instead of setting an assumption to prejudge the conditions of scenario. In the process, considering the lack of the priori, self learning with kernel strategy is used to estimate the possible solution. By enhancing the knowledge for distinguishing the $\alpha$ gap between the anonymous pixels, the process to categorize more anonymous pixels into foreground and background set with recursive $\alpha$ learning strategy. Under robust recursion, the matting solution is driven to reach the optimal solution.

Besides its effectiveness, the proposed scheme is user-friendly. Since the knowledge system is designed according to human experience, users can change the desired implementation directly by adjusting the parameters in knowledge system without knowing much about the theoretical part involved with the computations. It enables more users with different levels of expertise in drawing to handle and maintain the matting performance.

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## 5.3 Discussion and Summary

This chapter presented a differentiation solution of the target of interest using an adaptive learning strategy. The proposed solution, based on a recursive optimisation framework, successfully applies expert knowledge along with user experience into the matting. The experimental results indicate that the proposed adaptive learning algorithm performs stable matting under different conditions. The recursive learning scheme guarantees the convergence of the optimal solution. One of the unique goals of this research is to achieve balanced matting, which minimises anonymous, uncertain pixels by reducing the uncertainty of the solution. This can be seen as a special filtering that reduces the uncertainties in matting. Based on the given a priori, the uncertainty energies are adaptively scaled to avoid losing useful details and over-relaxing on trivial noises.

Based on the matting energy model, a recursive learning strategy is designed and applied to gradually reduce the uncertainty. The computing procedure is an iterative optimisation to find a series of suboptimal solutions within a specific energy scope given by the a priori and if the procedure is convergent, the optimal solution can be eventually achieved by the iterations. We proposed a design method using a set of theoretical proofs to guarantee the convergence of the procedure. The stability of the solution is guaranteed by the convergent properties of the learning operations, so that the suboptimal solution series is convergent to the fixed point as a unique solution. We also introduced a fuzzy knowledgebase using user-experience to accelerate the procedure. Using this knowledgebase to recognise the useful detail and trivial anonymous uncertainty, both the processing performance and user experience can be covered at the same time. Due to the robustness of the user experience, the fuzzy knowledge-based strategy enables the proposed scheme to adapt to different smoothness features and a priori assumptions. Iterative refining guarantees an adaptive approach to the optimal solution, thus making the scheme both robust and adaptive. When applying human experience, instructive cues (e.g., trimap) are needed for the recognition. This limits the automation. To automate the process to differentiate the target of interest, we proposed several strategies to generate the cue for the recognition, which will be given in detail in the following chapters (Chapter 6 and 7).

# Chapter 6

# Motion Analysis Based Target-Scene Differentiation

## 6.1 Introduction

In order to automate target differentiation, the system is required to be automatically aware of the target. Trimaps can be used for visual awareness, which triggers the computing for the Target of Interest (ToI) differentiation. Inspired by human vision, in this chapter we present a ToI differentiation solution by using motion as a cue.

One of the solutions for the automation of trimap generation is chroma-keying [120, 131, 402, 444, 539, 598]. To extend the adaptivity to the colour range of the foreground, robust layering based on colour space analysis is used to enhance the effect [54, 73, 623]. Modeling the background with hues that are drawn from a known probability distribution can improve the adaptivity as well [22, 116]. In some cases, to address the background constraints, special imaging techniques (e.g., thermo-keying [652]) are utilised to capture the image data with additional physical measurements. Despite their advantages in the relaxation of the monochromatic foreground and background constraints, these methods have disadvantages, such as the increase in the cost of special equipment and studio, or the constraints and limitations in colour space, etc. [360].

To address the constraints of chroma-keying, we apply Gaussian Mixture Models (GMM) [178,271] to build a vision-based stochastic processes model. The Gaussian model is also used to model the visual awareness of motion. Combined with the applications in multimedia [326,389,447,458], a scene layering approach with a standard camera is designed to perform the scene segmentation and synthesis. The feasibility of modelling a stochastic system with GMM needs a hypothesis that the dynamics of the information used in the analysis is obeying the Gaussian distribution, but this assumption is not always valid. In considering this, an adaptive learning strategy is designed to perform dynamical analysis based on motion-keying . With this adaptive learning processing, a motion keying showcase demonstrates the feasibility to adapt to uncertainties. The details are given in the next section.

## 6.2 Motion Based Dynamical Scene Layering

Pages 131-135 of this thesis have been removed as they contain published material. Please refer to the following citation for details of the article contained in these pages.

Liu, C. Z., Kavakli, M., McCallum, S., & Hamey, L. (2017). Motion-keying based dynamical scene layering with adaptive learning. in *ICCAE'17: Proceedings of the 9th International Conference on Computer and Automation Engineering*, 111-115.

DOI: 10.1145/3057039.3057085

## 6.3 Discussion and Summary

In this chapter, a strategy of motion based scene layering approach using ToI has been presented. The experiment shows that the proposed strategy can differentiate the target without any prior knowledge of the scene. The test shows that the results from the proposed strategy have better performance. Using adaptive learning and GMM modelling, the background is learned through scene updates and the pattern of the foreground is recognised gradually. After processing, the original scene has been decomposed into separate layers according to the motion. The foreground and background motions are detected and used to update the background knowledge reference and synthesise the scene. The residuals of each RGB channel remain smoothly stable during the whole process of scene layering. Although there is a residue of 2.25 bits, the improved motion-keying enables scene layering to adapt to various background lighting and colour changing conditions.

Using error analysis and adaptive learning, this dynamical scene layering scheme can be used in processing chroma-keying to reduce the request for a camera and a studio. It can also be applied to other applications of scene analysis (e.g., analytic panorama analysis for rehearsal and stage design with consideration of seats, settings, blocking, and lights). The proposed algorithm can be extendedly used in scene understanding with the simulation of motion-based visual awareness. However, the limitations of this strategy include:

(1) it can only layer the scene into a layer with motion and without motion;

(2) it may not work well when there is little motion in the captured vision information (e.g., static screen).

The first limitation (1) can be dealt by defining a motion measurement criterion to differentiate the various types of motion and project the corresponding motion pixels into different layers. This strategy focuses on the issue regarding how to define the object of interest to recognise, but may not work well for the second limitation (2). To address this issue, we propose a context-aware computing strategy for scenario analysis. The related works will be presented in detail, in the next chapter.

# Chapter 7

# Context Based Computing for Scenario Analysis

## 7.1 Introduction

This chapter presents a knowledge-based context-aware computing strategy for ToI differentiation and image fusion. To address the issue of automated dynamic scenario layering and target differentiation, we introduce depth and texture as visual contexts to model and simulate human visual awareness for scenario analysis.

One of the sources of visual awareness is stereo vision; digital stereo vision models the depth of a scene by matching pixels in images [275]. With any given pair of vision, the correlation between two sets of pixels can be used to calculate the disparity, thus modelling the depth with respect to the amplitude of the disparity on the corresponding position in the vision. This depth can be used as a reference for generating a trimap, as a form of pattern awareness based on stereo vision. Locally ambiguous patterns with occlusion or uniform texture occur while computing the disparity; these interfere with the depth estimation and depth differentiation results [295, 574]. Although global constraints provide extensive information for matching, the local uncertainties are too subtle and unnoticeable for machines to detect.

Based on the analysis above, we propose a method for modelling and processing the vision-based context-awareness while considering the uncertainties. By using context-based pattern analysis, the visual awareness is modelled with depth and texture as context-based triggers for scenario awareness [350]. Regarding the complexity of computation for comprehensive context mapping, we model the correlation between the mappings as overlaps in a logical hyper-space, as shown in Figure 7.1, where the logical overlap is the context. Considering the uncertainties

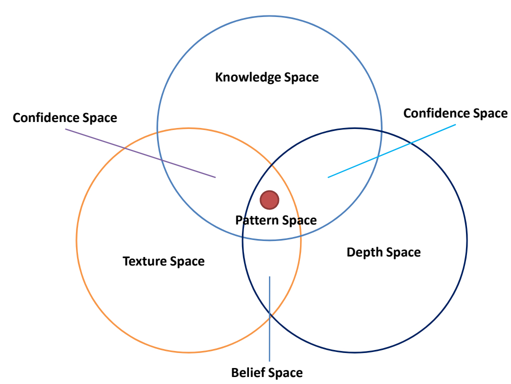


Figure 7.1: The hyper space of the logic in different context mapping.

in the dynamical interaction in the overlaps, we use a collaborative agent-based system for implementation. As shown in Figure 7.2, four main types of agents are used (Agent 0-3), connecting with a star topology in a multi-agent system (MAS) architecture. Agent 0 is responsible for the texture analysis and mixed reality fusion (MRF) tasks in scenario synthesis; Agent 1-3 take charge of depth mapping, context analysis, and stereo pattern decomposition processing.

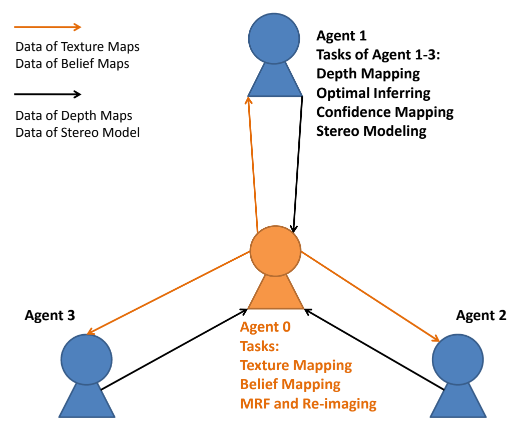


Figure 7.2: The Multi-agent Architecture and Related Tasks

The works are carried out based on the collaborative information processing framework proposed in Chapters 3 and 4. The implementation follows the design of agent-based collaborative information processing [351, 356]. This chapter mainly focuses on the related details about context-aware computing, which will be presented in the next section.

## 7.2 Knowledge Based Context-Aware Pattern Analysis

Pages 140-148 of this thesis have been removed as they contain published material.
Please refer to the following citation for details of the article contained in these pages.

Liu, C. Z., & Kavakli, M. (2016). Knowledge based pattern-context-aware stereo analysis and its applications. In: *2016 International Conference on Digital Image Computing: Techniques and Applications (DICTA)*.

DOI: 10.1109/DICTA.2016.7797058

## 7.3 Discussion and Summary

In this chapter, a scenario layering and target differentiation scheme based on context-aware stereo pattern analysis has been presented. Belief models and confidence mapping strategies are designed to deal with the uncertainty in the scene. The primary elements that are used to form the context awareness of texture and depth patterns, are the given depth and texture. The basic context patterns are decomposed into many combining sub-patterns to further clarify the patterns. By using human experience as the knowledgebase for pattern analysis, the system preserves the desired level of details while filtering out unreliable information. This method can be used for both the static and dynamical scenarios with the guarantee of a robust pattern for scenario layering.

Context cannot always be acquired accurately due to the limitations of the knowledge or modelling methods, therefore, we apply a multi-agent architecture to deal with the computation in hyperspace. The process has been implemented with a collaborative agent system; each agent in the system handles a logical area and the whole system can be divided into many sub-areas for interactive computing (Figure 7.3). The transition between the areas is represented by the correlations between the mappings. Various hardware and software modules are abstracted as several agents according to the roles they play. Each agent is dispatched with a certain extent of resources for computing. This scheme also provides a flexible architecture for scalable computing. The knowledge and functionality can be extended by accessing extra agents and the knowledgebase. Based on the knowledge assistant system, the system with knowledge-based co-pattern analysis can serve as a computer system that emulates the decision-making ability of a human expert. Using a collaborative process, the system can differentiate complex patterns with the support of the agents.

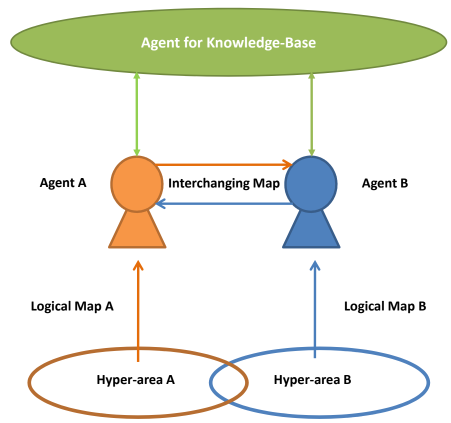


Figure 7.3: The interchanging dynamics within the multi-agent system for context mapping.

When considering the system as a part of the scenario, the system itself needs to be taken into account as an element of the context during the processing. In this case, the system is a part of the context, and corresponding awareness is the system's self-awareness of performance, which cannot be modelled and described in visual computing. This issue relates to research question RQ 4 How can we optimize the processes to improve the joint performance of human and computer in an iHCI system?. In the next chapter, we will focus on how to process the information, considering both user experience and system performance, to address context-aware computing from the system's perspective.

# Chapter 8

# User Experience and System Performance

## 8.1 Introduction

In this chapter, we mainly focus on the research question RQ 4 How can we optimise the processes to improve the joint performance of human and computer interaction in an iHCI system?, to study the balance between user experience and system performance. Firstly, we carry out a study on user experience and its influence on user behaviour throughout an interaction using vehicle driving behaviour as a proof of concept [344]. Factors, such as information, intention, mood, and stress, are taken into consideration to see how these affect a user's behaviour and decision making when driving. Two case studies and their results are given to show the relationships between information, intention, situation, and behaviour.

The issues and reasons for the drawbacks are discussed in order to demonstrate the importance of awareness analysis. The purpose of the behaviour-intention study is to validate the proposed optimisation process and provide practical evidence for the system design.

The scenario we chose to use during the study is driver behaviour under unfamiliar driving conditions. International drivers from countries with different traffic systems are often involved in car accidents [451,635], as they are unfamiliar with Australia's road rules. Changing the driving environment leads to a change in driving behaviour [17, 516] and how drivers respond to the situation influences the consequence. Cognitive ability varies with experience [455], age [646], and handedness [515], all causing differences in responses. However, drivers' perceptual skills, such as gaze and concentration on the road, can be influenced by high cognitive load [148,397].

An increase in cognitive load influences driver's motor skills in decision-making, such as steering control [486, 567], acceleration, and deceleration [265]. An interactive system, which provides information leading to good user experience can improve users' performance during decision-making. To prove this, we conduct a series of tests. Vision has a deep mental impact on human experience (e.g. [155]). Using a driving simulator, we investigate driver behaviour using vision as the type of information [501,648].

As for human-centred interaction, the concept of user-awareness has been used in information systems [128,306,452] to analyse behaviour and operations.

To enhance user experience in the system, we introduce Quality of Experience (QoE) as a criterion to measure users' satisfaction. Due to the increase of human-centred pervasive computing and ubiquitous networks, demand on high QoE in wireless communication has been growing [289, 521, 604, 667]. Therefore, we investigate wireless communication. QoE-aware systems with wireless communication provide a solution for understanding behaviour in smart interactions with a scalable assembly, but studies show that anthropomorphic responses are not efficient [170,420], because the proactive responses still lack not only user awareness but also user experience. Meanwhile, Quality of Service (QoS) may influence QoE [176]. Therefore, QoE is a user-focused performance measurement under a given QoS for a given product or service. There are constraints on network strategies due to the limited energy required to operate a network system [93,226,385]. The trade-off between QoE and QoS and the complexity of wireless communication [123,156] makes it difficult to reach an optimal level of QoE and QoS.

To measure QoS, we introduce network energy efficiency (NEE) [520] into the system. Mean opinion score (MOS) is used to quantify the QoE level [158, 268, 671], and MOS can be used to model the correlation between QoE-QoS. Although the relationship between QoE and QoS is complex [41, 192, 318], we find that features in the data are correlated with both QoE and QoS, which can be used to model their correlation. To analyse these relationships, we use Principal Component Analysis (PCA) [4] to extract the data features. Based on eigenvector decomposition and Karhunen-Lo‘eve transform (KLT) [146], the features extracted are used as parameters to represent QoS and QoE for building up the data-aware model and the implementation of QoE-QoS management.

Considering both user experience and system performance, optimal management is achieved. User experience is modelled as QoE based on MOS for computational assessment. QoS is used to measure the system performance. A data-aware computing strategy is proposed to hit the balance between QoE and QoS management. The awareness of the relationship between user experience and system performance has been modelled using Principal Component Analysis (PCA). This solution bridges the gap between QoE and QoS. Thus, Human & System-aware computing performance is determined by the normalisation of QoE-QoS [346]. The proposed computational solution performs three main types of QoE-QoS management (optimal QoE management, optimal QoS management, and QoE-QoS balance management). An experiment is presented to show the feasibility of the proposed solution.

## 8.2 Influence of User Experience on Human Behavior and Data-Aware QoE-QoS Management

Pages 155-166 of this thesis have been removed as they contain published material.
Please refer to the following citation for details of the article contained in these pages.

Liu, C. Z., Aliamani, H., & Kavakli, M. (2017). Behavior-intention analysis and human-aware computing: case study and discussion. In: *2017 12th IEEE Conference on Industrial Electronics and Applications (ICIEA)*, p. 516-521.

DOI: 10.1109/ICIEA.2017.8282899

Liu, C. Z., & Kavakli, M. (2016). Data-aware QoE-QoS management. In: *2016 11th IEEE Conference on Industrial Electronics and Applications (ICIEA)*, p. 1818-1823.

DOI: 10.1109/ICIEA.2016.7603882

## 8.3 Discussion and Summary

The results show that the information received can affect drivers' intention and decision-making. In the tests, we noticed that the subjects receiving the information prompt were less likely to take a risk than those without. This implies that the prompt can potentially convert those who are risk averse to risk takers. Therefore, information prompts can be used as an external informative incentive to trigger the internal psychological processes in user experience.

The user's mood and stress levels under unfamiliar driving conditions (UFDC) can work as an internal trigger to affect the driver's intention and affect their driving performance. When facing complexity and unfamiliarity in driving tasks, the situation can be gradually improved with sufficient experience after long training and practice, but informative prompts can also help. Human-centred information enables drivers to optimise their decision-making process and respond without hesitation. Therefore, the status of drivers can be adjusted with the information prompts so as to achieve optimal decision-making for different types of driving situations.

For QoE modelling, we used PCA and the idea of modelling the experience as an energy representation. The energy representation is modelled as a function of features. PCA is designed to perform an optimal feature extraction with maximal variance and minimum mean squared error. Due to the computability of the PCA based quantification, computer systems can be aware of the features with the measurement of the amplitude of the eigenvalue. Thus, we can implement data-aware computing for the QoE assessment. Therefore, we build the data-aware model based on eigenvector decomposition.

QoE can be approximately represented as the linear combination of the eigenvalues because it is positively correlated with the quantity of information, and the quantity of information is positively correlated with the eigenvalue of the image data. Once the eigenvalue matrix $\Lambda$ is ordered, the incremental function of QoE can be modelled as a function of the number of principal components k. After many tests, we choose Gauss error function to fit the correlation curve of the quality of experience and principal components. According to the empirical model, we found that the number of principal components k is positively correlated to MOS. Therefore, we bridge the gap between MOS and QoE with k, thus a PCA-based data-aware method can be used to measure the experience by the energy representation with respect to data features.

To model the QoS with the parameter k, network energy efficiency (NEE) is one of the criteria based on energy consumption for decoding and the useful energy in communication to assess the efficiency of the energy used in network communication, and when considering NEE under PER. After a certain amount of data load, the NEE is negatively correlated to the data load, while the experience is positive. Therefore, we define a QoE-QoS production, $Jc = MOS \times NEE$, to represent the efficiency of the balance regarding the solution. When MOS and NEE both reach the balance point, Jc reaches its maximum, which measures the optimal balance between the QoS and experience level.

This chapter mainly focused on the issue of user experience. A study on behaviour-intention analysis has been carried out with the consideration of human-aware computing in collaborative interaction design. The study [344] reveals the influence of relationship between behaviour and experience. The results show that the information conveyed to users during the operations affects their behaviour and intention. It also implies that the experience of a user, particularly the level of stress and mood, can be adjusted through appropriate information delivered by the interactive system. With a better understanding of a user's behaviour, proper information and augmented feedback (AF) can be used to improve the user experience of complex driving tasks associated with high cognitive load. The study serves as a base for behaviour-intention analysis and human-awareness modelling in the iHCI. The conclusions can be used in modelling computing awareness using the analysis of behaviour-intention in future works.

In order to understand user experience, we apply the QoE as a parameter to model the computing awareness of user-experience. We also combine QoS as a parameter to model the computing awareness of the system performance to design a data-aware computing strategy to balance user-experience and system performance. A subspace learning method is applied to model the correlation of QoE-QoS unification. Principal Component Analysis (PCA) can be used to simplify the awareness model as well as the operations to perform QoE-QoS management. The system only needs to control the joint handler k to manage the QoE and QoS. By the bridge spanned over the QoE and QoS, the processing of

QoE-QoS unified optimisation has been proposed and performed in normalised scale space.

This implementation answers research question 4. The results show the feasibility of this strategy, and it is cost-effective to implement. It implies that other subspace learning strategies can also be introduced into the design to make it affordable for the system to arrange computational resources. The study also implies that this data-aware scheme for QoE-QoS management can be further extended to a large-scale processing for assessing user experience and system performance. By adjusting the joint handler k, designers can customise the flexibility of the system.

This experiment uses wireless sensor media network (WSMN), a type of distributed network system for media communication, as proof of concept. Actually, a distributed database system and a knowledge management system are required for both extensive development and flexible access, especially when the scale of the system is large. However, in that case, the issue is how to manage the knowledge and database; information security and privacy management would be problematic when the interaction environment is open due to the distributed and flexible access. These issues would be not only harmful to user experience but also detrimental to system security and user privacy. We will focus on the solution to these problems in the following chapters.

# Chapter 9

# User-Identification Based Database Management

## 9.1 Introduction

This chapter covers two main issues,

(1) user-aware computing regarding user-identification applications, and

(2) research question RQ 5: How can we manage the intelligent system when applying a flexible structure in dispersed, distributed but coordinated information processing?

The first issue relates to user-aware computing in agent-based design and implementation (Chapter 4), including the user identification agent in the user identification group (UIG) and user-feature learning agent in the user-feature learning group (UFLG) [356]. We apply subspace learning to perform feature learning and user identification. The main source of data for user identification is the photos of users' faces. PCA is used to perform the subspace learning and data analysis [348]. The agent's awareness of the user, in this case, is modelled as a set of features.

Aiming to answer research question 5, we mainly focus on the issue of database management in a distributed system with a flexible structure. Considering the flexible access of the collaborative information processing in the agent-based design, we design a scalable strategy for feature learning, data querying, and knowledge updating in the distributed database [352]. This strategy contributes to the design and implementation of database management in the database management group (DBMG) [356]. Therefore, the study in this chapter is used to implement user-aware data management through the interactions between UIG, UFLG, and DBMG based on the user information database and related data operation.

In this research, feature learning, which has been widely applied in many intelligent data systems (e.g. [114, 165, 279, 280]), is the base to implement the user-identification. Most of these data systems are centralised but considering the flexible assembly in distributed databases [125, 138, 367], knowledge systems may allocate and deploy the dispersed data stored in multiple interconnected computers (e.g. [11, 20, 235, 500, 506]). When data is updated frequently, the knowledgebase needs to re-learn the updated features [43, 186, 310], which is inefficient for a large-scale system, because it is time-consuming for data process and synchronisation. Considering outliers and noise interference [13], the uncertainty exists during the data acquisition (e.g. [386, 386, 612]), which further limits the efficiency in scalable data feature extraction.

Subspace learning has provided solutions to the large-scale feature learning [278, 340, 342, 345, 508, 675]. Incremental subspace learning [345, 508, 675] is one of the typical technologies used to deal with large scale subspace learning, which breaks down the workload into pieces. The data is updated by learning piece by piece, but the database still needs to be in its entirety.

Another method is blocking subspace learning [342], in which the feature space of each data block is obtained respectively by training. Furthermore, the distributed PCA also serves as a feasible scheme to cope with the big data computation [278, 340]. These methods share the workload through workflow segmentation thus reducing the scale of computation. However, the database still needs to work in its entirety rather than as a dispersed structure. Inspired by the methods above, we design a scalable learning strategy for a distributed knowledge system. The next section covers a comprehensive literature review of PCA and its extensions and proposes a scalable learning strategy based on subspace learning and their applications to visual computing, as a solution to user identification implementation.

## 9.2 User-Identification with Subspace Learning Based Scalable Strategy

Pages 175-229 of this thesis have been removed as they contain published material. Please refer to the following citation for details of the article contained in these pages.

Liu, C. Z., & Kavakli, M. (2016). Extensions of principle component analysis with applications on vision based computing. *Multimedia Tools and Applications*, 75(17), p. 10113-10151.

DOI: 10.1007/s11042-015-3025-3

Liu, C. Z., & Kavakli, M. (2016). Scalable Learning for Dispersed Knowledge Systems. In: *MOBIQUITOUS 2016: Proceedings of the 13th International Conference on Mobile and Ubiquitous Systems: Computing, Networking and Services*, p. 125-134.

DOI: 10.1145/2994374.2994395

## 9.3 Discussion and Summary

This chapter mainly focused on subspace learning for user identification and scalable strategy for flexible data processing management. To address the first issue, we focus on PCA and its applications in vision-based computing, including image compression, visual tracking, image recognition, and super-resolution image reconstruction. By discussing the underlying mechanism of PCA, significant factors involved in subspace training are studied with the consideration of the principal components' energy, residuals assessment, and decomposition computation.

As for user-aware computing for user-identification, we model users' awareness by decomposing the users' face data as a set of eigenvalue and eigenvectors in an orthogonal linear subspace. This decoupling decomposition is also the primary procedure for feature learning. Computing awareness can be stored as a type of knowledge of users. For identification, the system loads the knowledge and uses it as a set of mapping vectors to project the particular input face data onto the subspace. Each projection points to a unique user. After measuring similarities in the subspace, the candidate with the least residual projection will be identified as the targeted user.

With an aim to address research question RQ 5. How can we manage the intelligent system when applying a flexible structure in dispersed, distributed but coordinated information processing?, we model the dynamical awareness of the system processing as a stochastic process related to the target state $\xi$. For distributed database updating, the learning for each local computing entity is independent without coupled information. Due to the lack of coupling, the cross-correlation part of the knowledge between computing entities in the global knowledge of the whole database is missing.

The learning for each group in the distributed database to form the knowledge only covers a part of the complete awareness of user-identification, which makes the knowledge dispersed. With the $\xi$ instructed processing, the state of the target input will be used to instruct the data processing to refine the knowledge loaded from a distributed database, while the trivial candidates will be excluded. After several exclusions, the candidate with the most similarities will be preserved for the next round of learning to update the knowledge base. The updated results of each round will be stored in the distributed database, thus making the database and knowledge system scalable. The cross-correlation will be learned by each entity with this updated learning procedure to form the scalable awareness.

In the tests, face recognition is taken as the test for user-identification. We combine the scalable strategy with the standard PCA and compare the result with other methods, such as Eigenface, Fisherface, DLDA, PCA+LDA, and KPCA. The performance analysis shows that the proposed scalable strategy makes the dispersed knowledge system work as well as a centralised one, with KPCA regarding the recognition rate, and the learning time of the proposed strategy is the least among all. Different subspace learning strategies would influence the efficiency and effectiveness of the system, which suggests that the performance can be further improved if a better subspace learning strategy is applied.

# Chapter 10

# Confidential Data Exchange with Cryptographic Tunnel

## 10.1 Introduction

This chapter addresses research question RQ 6: How can we guarantee information security in an iHCI system for mixed reality? Security, one of the significant issues in relation to both users' privacy and system operation in iHCI applications, helps to enhance the usability of confidential features in end-user applications. Database management processes with the support of user identification- (Chapter 9) and biometrics (such as facial or fingerprint recognition) can identify a particular user for data access and system operations. This is a convenient solution for ordinary users who do not have much expertise in privacy management and database operation.

Since vision is the main source of information in the VR and MR scenario in this research, vision-based media WSNs [440,465,484] are needed to bring visual information to the system; in this case, Wireless Sensor Media Networks (WSMNs) are used. As part of the design to access human-centred smart interaction, the WSMNs also help to improve scalability and flexibility [364,379,630,644,657]. The network can operate as a real-time monitoring system for understanding the target behaviour, but malicious hackers would be able to gain unauthorised access to data in an open system environment.

Due to the dramatic increase in attacks and the scarcity of computational resources for defence against them [147, 467, 536], security is a significant issue for applications of sensor networks in information exchange [89, 248]. Cyberespionage is one such harmful intrusion [311, 551, 660], in which a spying node is put into a sensor network, masquerading as a legitimate sensor and overhearing the system. The spying node can also be responsible for a Sybil attack [147, 430], key-recovery by brute force, hill-climbing [187, 392], or plaintext attacks [485], intruding into the system by illegitimately claiming multiple identities, or even taking over the whole network through a Distributed Denial of Service attack (DDoS [77, 410, 536]). Therefore, protection against attacks is important for both the security of the system itself and the privacy of users.

In this context, we consider a case of an open system environment with potential threats to users' privacy and system security (e.g., malicious overhearing, impersonation, and key recovery attack). In this environment, the data-exchange components in the mixed reality system, including transmitters, receivers, and data capsulation, are modelled and simplified as agents in a media communication network. Public key cryptography (PKC) [223, 473] is introduced into and combined with confidential communication and chaotic ciphering technology to guarantee data security and privacy for the communication in the network [18, 143, 160, 503]. Wireless communication conditions are also considered, which turns the simplified system into a WMSN. Considering the risks of malicious attacks and overhearing during data exchange and processing, we design a channel management strategy using chaotic cryptography and public keys to provide data-awareness for information security and confidential communication [353].

This chapter mainly aims to support the design and implementation of a confidentiality agent for data coding and decoding (see Chapter 4). In this chapter, we simplify the processes for decoding and encoding as packing and unpacking operations. We mainly focus on the primary processing of authentication and cryptography for confidential communication, access authentication and masquerading intrusion detection on a system level.

## 10.2 Confidential Data Communication with Chaotic Cryptographic Tunnel

Pages 234-256 of this thesis have been removed as they contain published material.
Please refer to the following citation for details of the article contained in these pages.

Liu, C. Z., & Kavakli, M. (2019). A data-aware confidential tunnel for wireless sensor media networks. *Multimedia Tools and Applications*, 78, p. 26941-26963.

DOI: 10.1007/s11042-017-4395-5

## 10.3 Discussion and Summary

In this chapter, we design a strategy for a media network system to perform data-aware confidential communication and access authentication using chaotic cryptography and public key management. The work is mainly applied to the design and implementation of the confidentiality agent [356]. Based on the data exchanged in the network, each node with an embedded agent gains knowledge of the context related to the devices connected with it. The embedded agent performs authentication with the support of Public Key Cryptography (PKC) in the chaotic tunnel. A chaotic compound dynamic is used for ciphering and deciphering as a base for the encrypted tunnel. Information security is enhanced through mixed and hidden encryption. A simulation is presented, and the results show that the proposed strategy can protect the data using PKC-based authentication and detection of masquerading attacks.

The tests show that the proposed strategy is more adaptive and robust in terms of the correlation distribution of the plain text images after encryption. At the same time, the proposed solution overcomes the potential for secret-leaking outliers due to the cipher blocking strategy. As for visual representation, the information has been randomly scribbled in plaintext in the space domain after encryption. With the support of PKC and keyspace, the proposed solution embeds anti-counterfeiting information into the encrypted data via hash-based data-aware confidentiality, which can authenticate and identify cyber-espionage nodes and malicious tampering behaviour in the network. Combined with hardware security and key encapsulation, this also enhances access security.

This chapter presents a self-aware and context-aware strategy for data exchange and access management on a system level. The awareness is modelled in a data representation as a series of codes generated by the PKC system, chaotic dynamics, and hashing of the data. While exchanging data in the network, the inter-operation enables the nodes to be aware of the accesses via the feature obtained by data analysis, which implements self-reflection and self-adaption of self-awareness. The results of the analysis are used to design a reasoning awareness model as a data-triggered action such that, if the results of analysis from the nodes do not match each other, the data source node will be detected as masquerading and reported to the PKC authentication system.

The work in Chapter 9 can be used to provide a user-awareness computing strategy for user access to the database management. Based on this work, the awareness of the authentication can be further extended to mixed groups of human and non-human agents with hybrid target-awareness, self-awareness, and context-awareness. In the next chapter, we provide a more comprehensive synthesis of these components. An application of mixed reality fusion is presented as a showcase to demonstrate the feasibility and performance of the iHCI system.

# Chapter 11

# System Synthesis and Implementation with An Application of Mixed Reality Scene Fusion

## 11.1 Introduction

So far, we have modules of the agent-based system in Chapter 4, including:

(1) knowledge based enhanced matting (Chapter 5) for enhanced matting agent in target-of-interest differentiation group (TOIDG);

(2) motion analysis based target-scene differentiation(Chapter 6) for scene-layering analysis agent in TOIDG;

(3) context based scenario analysis (Chapter 7) for context-pattern analysis agent in TOIDG;

(4) user experience and system performance analysis (Chapter 8) for QoE-QoS Management Agent in sensing group (SG);

(5) user-identification based database management (Chapter 9) for user-identification agent in user identification group (UIG) and user feature learning agent in user feature learning group (UFLG);

(6) confidential data exchanging with chaotic tunnel (Chapter 10) for confidentiality agent.

In this chapter, we use the system and functionalities as a showcase to demonstrate the feasibility of the design. Based on the agent-based system design presented in Chapter 4, we apply the module above to address the issues mentioned in Chapter 3, including mixed reality fusion, QoE-QoS management, confidentiality, and security. The test results for each module are given to show the performance of the solution.

## 11.2 System Synthesis and Demonstration

Pages 261-274 of this thesis have been removed as they contain published material. Please refer to the following citation for details of the article contained in these pages.

Liu, C. Z., & Kavakli, M. (2017). An agent-aware computing based mixed reality information system. *International Journal of Virtual Reality*, 17(3), p. 1-14.

DOI: 10.20870/IJVR.2017.17.3.2896

## 11.3 Discussion and Summary

This chapter demonstrates an agent-based system for collaborative information processing in mixed reality. Based on the iHCI framework, functionalities including context pattern analysis, data-aware confidential communication and QoE-QoS management are implemented. We use an Agent-based design [356]. A multiple view camera system is designed and applied to capture visual data of users and scenes. Users are modelled in the virtual world with their facial features as a set of feature data and 3D models. The users' information is protected using the data-aware confidential communication strategy. Hash is used to implement awareness of agent to identify the access.

A context-aware computing strategy for recognising patterns is applied to simulate human awareness as a process of stereo pattern analysis [350], and subspace learning is used to estimate user experience [346]. Based on the balance between user experience (QoE) and communication efficiency (QoS), the QoE-QoS management agent optimally compresses the data to improve the efficiency of communication.

In mixed reality fusion (MRF), the system recognises the portrait of users in association with context-pattern analysis. A $\xi$ process [352] is applied with the subspace learning strategy to perform a scalable knowledge system for feature learning to identify the users, and PKC is proposed to perform confidential communication with ciphered data while detecting malicious behaviour [353]. Via data management with the support of user identification-, the system links the corresponding identification to each user's stereo model. After scene fusion processing, the recognised virtual user's 3D models are merged with the real-world object as a real-virtual entity, building a scene of the MRF object. The outputs of each module are given to show the feasibility of the solution. The results show that the system successfully performs collaborative information processing for mixed reality via the cooperation among the agents.

# Chapter 12

# Conclusion and Future Works

This chapter concludes the thesis, providing an overall evaluation. The answers to the research questions RQ 1 to 6 (listed in Chapter 1) have been presented in conclusion. Contributions of the thesis involve an agent-based system design, the target of interest differentiation, knowledge modeling and management, QoE-QoS management, and system synthesis. These contributions have been summarized and a discussion on the findings and limitations have been provided, and future works are given for further research planning.

## 12.1 Conclusion

This thesis presents techniques for an iHCI framework using agent-based computing and collaborative information processing in mixed reality applications. We introduce a number of enhancement as discussed in Section 1.4.1, Chapter 1 for visual computing, sensing system performance, and sensing human-system performance. Six research questions related to the development of an iHCI framework for mixed reality as listed in Chapter 1 include issues related to system design, target of interest, human knowledge and user-experience, QoE-QoS management, system management, confidentiality and security, and agent-awareness. Each of these issues are addressed in this thesis in various chapters and publications as explained in Section 1.7, Chapter 1 (see in Table 1.3). Related applications as defined in the system architecture are presented in detail in each chapter.

## 12.2 iHCI Framework

Figure 12.1 shows the primary framework for the system implementation. Three main enhancements in visual computing, sensing system performance and sensing human-system performance are supported by the target of interest differentiation, evaluation of user experience and context-based computing. The main elementary functions include image fusion, simulation of the attention to the target, user experience evaluation, joint performance evaluation, device authentication, and the processing related to structure and operations. These are implemented by performing Human-Visual Awareness Simulation (HVAS), System-Performance Awareness Simulation (SPAS) and Human-System Joint Performance Context Awareness Simulation (HSPCA) for context of interaction (CoI) and context of system environment (CoSE). The main modules of HVAS, SPAS, and HSPCA are shown in Figure 12.2.

In Figure 12.2, we can see that the modules in HVAS are mainly related to TID and EUE. QoE Modeling (QoEM) is mainly based on the knowledge of the users' visual assessment of quality of experience using Mean Opinion Score (MOS). Processing including enhanced matting (EM), motion keying (MK), stereo pattern analysis (SPA), and dynamical scene layering (DSL) are related to visual computing. Some strategies of computational intelligence such as adaptive learning, and fuzzy knowledge system are required for system implementation.

In SPAS, modules including Agent-Based Data Management (ABDM), Collaborative Process Coordination (CPC), and Agent-Based Application Management (ABAM) perform the functions for systematic operations with simulating the awareness among the computing entities. Device Authentication (DA), Chaotic Confidential Tunnel (CCT) and Public Key Cryptography (PKC) simulating the authentication awareness for security and confidentiality during the data-exchanging. Optimal QoS Management and Scalable Learning Strategy (SLS) simulates the awareness of the performance of the system from the perspective of quality of service. These modules are mainly related to CoSE.

With the support from HVAS, modules in HSPCA combine the functionalities of SPAS to perform the task for both CoI and CoSE. Optimal QoE-QoS Management is performed by combining QoE modeling in HVAS and optimal QoS management in SPAS for CoSE. With the support of ABDM, CPC and ABAM, Mixed Reality Fusion (MRF), Face Detection (FD) and User Identification (UI) are performed by combining enhanced matting, motion keying, stereo pattern analysis, and scene layering for CoI. With the support of Device Authentication (DA), Chaotic Confidential Tunnel (CCT) and Public Key Cryptography (PKC), Masquerading Detection (MD) are performed with the support of User Identification for both CoI and CoSE.

Table 12.1 shows the methodological relationships that involve main modules (Mod.), enhancements (Enha.), functions (Func.), main supports (MSup.), attributes (attr.), and related chapters (chap.) and publications (publ.) listed in Section 1.7. In the table:

- VC stands for Visual Computing, TID for target of interest differentiation,
- CBC for context-based computing, EUE for evaluation of user-experience,
- SSP for Sensing System Performance,and SHSP for Sensing Human-System Performance,
- TID for target of interest differentiation, CBC for context-based computing,
- EUE for evaluation of user-experience, AL for Adaptive Learning,
- FKS for Fuzzy Knowledge System, SL for Stochastic Learning,
- PCA for Principal Component Analysis, ABM for agent-based modeling,
- MAS for multi-agent systems.

## 12.3 Findings

This section summarizes the findings related to research questions listed in Section 1.6.1.

Table 12.1: The Methodological Relationships of iHCI

| Mod. | Enha. | Func | MSup. | Attr. | Chap. | Publ. |
|---|---|---|---|---|---|---|
| EM | VC | HVAS | AL, FKS | TID | 5 | 4 |
| MK | VC | HVAS | AL, SL | TID | 6 | 5 |
| SPA | VC | HVAS | AL, FKS | TID | 7 | 6 |
| DSL | VC | HVAS | AL, FKS, SL | TID | 6,7 | 5,6 |
| QoEM | VC | HVAS | MOS, PCA | EUE | 8 | 8,11 |
| ABDM | SSP | SPAS | ABM,MAS | CoSE | 4 | 3 |
| ABAM | SSP | SPAS | ABM,MAS | CoSE | 4 | 3 |
| CPC | SSP | SPAS | ABM,MAS | CoSE | 4 | 3 |
| DA | SSP | SPAS | PKC, ABDM, CPC, CCT | CoSE | 4,10 | 10, 3 |
| SLS | SSP | SPAS | PCA, SL | CoSE | 9 | 9 |
| MRF | VC,SHSP | SPAS | EM, MK, SPA, DSL | CoI | 6,7,11 | 5,6,12 |
| FD and UI | VC,SHSP | SPAS | FD, EM, PCA | CoI,CoSE | 11,9 | 7,9,12 |
| MD | VC,SSP,SHSP | SPAS | PKC, ABDM, CPC, CCT | CoI,CoSE | 10 | 10,3 |
| OQoE-QoSM | VC,SSP,SHSP | SPAS | PCA, SL | CoSE | 8 | 8,11 |

### 12.3.1 Research Question RQ 1: What are the major components of an iHCI framework for mixed reality?

Chapter 3 and Chapter 4 answer RQ 1 by presenting an iHCI framework and discussing the details of the system design.

Chapter 3 presents MIXER system architecture [351] for mixed reality to answer how these elements are integrated. An application of military training has been introduced as an example that discusses aspects that need to be enhanced [351]. Related components, such as smart helmet and smart gateway used in the system, are also presented to give a tangible or visible form to the framework. This mainly addresses the question regarding the main elements of the system.

MIXER, eMR, and iHCI are closely related concepts but different to each other (see Fig.12.3). MIXER is an interactive system for mixed reality; iHCI is an agent-based system solution to support MIXER; eMR is a sub-system of MIXER focusing on interaction oriented functional computing. Figure 12.4 shows the eMR with the support of iHCI. It can be seen that iHCI provide eMR with computational intelligence to perform interaction for various applications.

Chapter 4 presents iHCI framework for mixed reality. Different types of agents and agent-groups for eMR have been discussed to show what the system looks like [355]. Using agent-aware computing, modules for enhanced matting, user identification and QoE-QoS management, have been presented to show the main functional elements of the system [355, 356]. Issues and solutions related to collaborative information processing have been discussed with a task scheduling strategy.

### 12.3.2 Research Question RQ 2: How can we simulate human's visual processing in iHCI to differentiate the target of interest in mixed reality?

To answer the research question RQ 2, Chapter 5 to Chapter 7 present three schemes for target pattern of interest recognition, including human instruction (user's markup), motion analysis, and context based pattern analysis respectively.

Chapter 5 presents a matting scheme for target-of-interest differentiation.We have found that the results vary depending on the both matting algorithms and markups. Therefore, a matting solution based on human knowledge system and adaptive learning strategy is designed to guarantee robustness of differentiation [357]. The uncertainty in knowledge, user-experience, processing and solutions, are processed by fuzzy adaptive learning using the recursive $\alpha$ optimization framework. The experimental results show that the stability of the differentiation has been enhanced by the proposed solution.

Chapter 6 presents a scene differentiation framework using motion analysis. We have found that it is difficult for the system to recognize the target when knowledge of background is missing. Therefore, an adaptive learning strategy based on Gaussian Modeling (GM) has been designed to reconstruct the background knowledge gradually during the processing [360]. The keying results shows that the system can adapt the uncertainty using the motion differentiation for scene layering. This can be performed by introducing an adaptive learning algorithm with a kernel updating strategy. The proposed solution has the potential to perform a layering task without the prior knowledge of the scene.

Chapter 7 extends pixel based learning to context based learning for target-of-interest differentiation. Depth and texture are selected as two main types of information to model context awareness. With a knowledge-based inference engine, human experience can be used to model the correlations between the context. Using a context based pattern analysis strategy, an application of stereo pattern analysis for scene fusion is presented to show the feasibility of this approach. Context awareness has been modeled as context based belief. An enhanced learning strategy enables the system to process the ambiguous patterns and refine the system's confidence by using context based belief to resolve the uncertainty [350]. The results show that potential patterns can be differentiated and rebuilt as an extracted stereo model using context awareness.

### 12.3.3 Research Question RQ 3: How can we design a knowledge-based information system to model human experience in mixed reality scene fusion?

Chapter 5 to Chapter 7 contributes to answering RQ 3 by presenting a solution for knowledge modeling and updating adaptive knowledge. A fuzzy logic system using adaptive learning and knowledge based inference is proposed and applied [350, 357]. With the introduction of an enhanced learning strategy, each iteration of learning provides a reference for the system to refine the knowledge before the next update. This simulates the procedure of humans' visual computing to form the knowledge of scene and target.

To model and apply the human knowledge to target differentiation, the experience of different types of user, including graphic designers, photographers, and amateurs, has been collected to build an inference engine. By adaptive learning and reasoning, the uncertainty of priori knowledge and experience in the operations have been reduced to guarantee the stability of the differentiation results.

### 12.3.4 Research Question RQ 4: How can we optimize the processes to improve the joint performance of human and computer interaction in an iHCI system?

To answer research question 4, we focus on QoE and QoS, where QoE refers to the human side of the joint performance and QoS the system side. Chapter 8 presents a framework to reach the optimal balance between QoE and QoS. QoE is modeled by MOS (mean opinion score). We have found that the main reason for the difficulties of the system to coordinate QoE and QoS concurrently lies in the nonlinearity of the relationship between the two.

Aiming at this, the limitation of MOS and asymmetric correlation between MOS and QoS has been discussed. We proposed a normalization method using Principle Component Analysis (PCA) and nonlinear transform [346, 348]. MOS and QoS have been aligned in a normalized scaling space. This allows us to process these two indices in the same computational system. Based on this, a unified data-aware QoE-QoS optimization strategy is proposed. The unified optimization overcomes the difficulty in balancing the QoE-QoS to improve the joint performance.

### 12.3.5 Research Question RQ 5: How can we manage dispersed, distributed but collaborative information processing in an iHCI system?

Research question RQ 5 has been mainly addressed by Chapter 4 and Chapter 9.

Chapter 4 provides an agent-based system design. The proposed task scheduling method is used as a task-oriented self-organization solution for a distributed agent system in iHCI [356]. A multi-task scheduling and concurrent transaction coordination for collaborative information processing are also designed and tested.

Regarding knowledge management using a dispersed structure, Chapter 9 proposes a scalable learning scheme with the $\xi$ process to perform feature acquisition and update [352]. By using the proposed scalable scheme in a dispersed knowledge system, updates can take place only for the entity to be updated, rather than the whole knowledge system. Chapter 10 also answers this question in terms of information security. It provides an authentication solution for coordinating the distributed agents in the system.

### 12.3.6 Research Question RQ 6: How can we guarantee the information security in an iHCI system for mixed reality?

Chapter 10 answers research question RQ 6 by providing a data-aware scheme for confidential communication and data security. Regarding confidential communication, a data-aware attack-detection strategy performs self-awareness for authentication and attack detection by using public key cryptography [353, 355]. A chaotic tunnel is built to enhance the security by a PKC combined chaotic ciphering strategy. Security factors, such as scrambling in space domain, distribution in frequency domain, and sensitive key space, have been evaluated. The security performance has been improved by reducing the correlation between the plaintext and cryptography text. Our experimental results show that the scheme is able to protect the system against the impersonal intrusion and key recovery attacks simultaneously.

## 12.4 Contributions

The main contributions of this research include:

- a framework of an iHCI system;
- an architecture of agent-based collaborative information processing;
- a system synthesis for mixed reality fusion application;
- a method for target of interest (ToI) differentiation using enhanced matting and recursive learning;

- a method for dynamical layering using motion detection and adaptive learning;
- a method of context-based awareness modeling and pattern analysis for TOI differentiation;
- a method for quality of experience and quality of service balancing using data-aware computing and user-experience estimation;
- a method for user identification based knowledge database management;
- a method for system security aware communication using confidential tunnel and data-aware masquerading detection.

Supportive modules for the iHCI system have been designed and implemented with the proposition and improvement of the related methods. The main modules and methods include:

- target of interest (TOI) differentiation using enhanced matting and recursive learning;
- dynamical scene layering and fusion using motion detection and context-pattern analysis;
- context-based stereo pattern analysis for TOI differentiation;
- quality of experience and quality of performance balancing using data-aware computing and user-experience estimation;

- user identification based knowledge database management;

- system security aware communication using confidential tunnel and data-aware masquerading detection.

Each module is designed with the related methods, and relevant test proof of each module and synthesis of the system are given to show the feasibility of the scheme.Each module is designed using the methods mentioned above. The relevant test proof of each module and synthesis of the system are given to show the feasibility of the framework.

Based on those modules, the main functionalities of the iHCI system include

- mixed reality fusion (MRF)

- target of interest differentiation

- dynamical scene layering

- dispersed knowledge management

- QoE-QoS optimal management

- confidential communication

- masquerading detection

The detailed contributions in methodology and implementation are listed in table 12.2.

Table 12.2: The Main Contributions

| Contributions | Chapter | Publication |
|---|---|---|
| Framework design of MIXER | 3 | [351] |
| Systematic agent-based iHCI system for eMR | 4 | [355, 356] |
| agent-based collaborative information processing | 4 | [355, 356] |
| Fuzzy knowledge based Adaptive learning strategy | 5 | [357] |
| Knowledge based Enhanced Matting | 5 | [350, 357] |
| Gaussian kernel based adaptive learning strategy | 6 | [360] |
| Motion-Keying Solution | 6 | [360] |
| Learning confidence modeling and optimization | 7 | [350] |
| Pattern-context-based stereo pattern analysis | 7 | [350] |
| Dynamical Scene Layering | 6, 7 | [350, 360] |
| PCA-based nonlinear subspace normalization | 8 | [346, 348] |
| Data-aware QoE-QoS optimal management | 8 | [346] |
| $\xi$-process-based scalable learning scheme | 9 | [352] |
| Chaotic tunnel for confidential communication | 10 | [353] |
| Data-aware masquerading detection solution | 10 | [353] |
| User identification based knowledge database management | 11, 9 | [348, 352, 354] |
| An iHCI demo system with its applications on MRF | 11 | [354] |

## 12.5 Evaluation of Methodologies

This section discusses the evaluation of the main methods proposed and applied in this thesis, including:

- Knowledge-based adaptive fuzzy strategy for ToI differentiation
- Gaussian kernel-based adaptive learning strategy
- Data-aware QoE-QoS optimal management
- $\xi$-process-based scalable learning scheme
- Chaotic PKC-based confidential communication

Three main types of evaluation are employed: goal based, process-based and outcomes-based. For the goal-based evaluations, we measure if the objectives of each proposed method have been achieved. For process-based evaluations, we mainly analyse the features of the methods in terms of the process. Outcomes-based evaluations are presented with specific criteria corresponding to each method to examine quantitative impacts. Comparative studies for each method is also presented with the evaluations.

### 12.5.1 Knowledge-based Adaptive Fuzzy Strategy for Target of Interest Differentiation

In Chapter 5, a fuzzy knowledge system using an adaptive learning strategy is proposed and applied to enhanced matting [350, 357]. To address uncertainty, the number and energy of the anonymous pixels are considered as an objective for optimisation to reduce the uncertainty of matting and a recursive $\alpha$ learning scheme is designed to guarantee the uniqueness of the optimal solution. A comparative study is conducted between closed-form matting, learning-based matting, and the proposed adaptive learning strategy.

For the goal-based evaluation, the proposed strategy successfully performs matting with cleaner target-of-interest segmentation compared with closed-form matting and learning-based matting. For process-based evaluation, we prove the stability and uniqueness of the solution of the matting process with the proposed strategy. The theoretical analysis shows that the proposed algorithm can guarantee the uniqueness of the solution with a stable convergence. The proposed theorems can also be used as design principles of the convergent optimisation for enhanced matting. Outcomes-based evaluations are given with specific criteria, including the dimensions of the segmentation mask $\alpha$, the energy of the mask $\|\alpha\|$, and macro energy dimension product (MEDP) to measure the uncertain pixels remaining in the segmentation mask after differentiation processing. The tests show that the overall differentiation results obtained by the proposed method have the lowest uncertainty among the three methods based on all three criteria.

### 12.5.2 Gaussian Kernel-Based Adaptive Learning Strategy

In Chapter 6, an adaptive learning strategy (APLS) based on Gaussian mixed-models- is proposed and applied to motion keying. The strategy implement the non-parameter stochastic kernel learning for motion modelling and updating [360]. Based on a Gaussian mixed model for dynamical scene layering tests, comparisons are drawn between processing with and without the proposed adaptive learning strategy .

For goal-based evaluation, the observation shows that the proposed strategy provides clearer segmentation between layers than the GMM-based background subtraction method. For process-based evaluation, we find that the proposed strategy improves the adaptivity and robustness of the system in differentiating the foreground from the background by motion without the need for the original background frame. However, the adaptive strategy needs extra time to process learning with this method than without it.

MSE-based evaluation is applied for the outcomes-based evaluation. The result shows that the background and foreground reconstructed by APLS have less residual compared with the GMM without the proposed adaptive learning strategy. The residual of the method using the proposed strategy remains stable at the level of 2.25 bits; without the proposed method, it appears to increase with the frames. Based on the evaluations above, it can be seen that the design applied in the chapter improves the adaptivity and stability of the system during differentiation of the target by motion but extra computing resources are needed to complete the adaptive learning strategy.

### 12.5.3 Data-aware QoE-QoS optimal management

In Chapter 8, a data-aware QoE-QoS balanced strategy is proposed with the consideration of the tradeoff in network resource for data communication [346]. A QoE model using principal-component-analysis-(PCA) is built based on the energy of the data. With the energy quantification, the corresponding QoS model is built based on network energy efficiency. Based on the connection between these two models in the energy model, the bridging QoE-QoS model is proposed to manage the balance between these two criteria. Comparisons are drawn between the optimal QoE, optimal QoS and balanced management.

For goal-based evaluation, the experimental results as a proof of concept show that the proposed strategy successfully strikes a balance between the QoE and QoS in image communication. For process-based evaluation, the tests show that the proposed method is able to obtain an optimally acceptable effect when performing an image communication under a resource-limited network. Outcomes-based evaluations are given with specific criteria, including MOS, NEE, and QoE-QoS product $J_C$. With the given parameters of the network, the test shows that the data compression result obtained by the proposed QoE-QoS balancing strategy is highest in $J_C$, which means that the performance in service and user experience reaches the optimal level at the same time under the given network conditions, and the optimal balance point based on the number of principal components can always be found automatically by the proposed QoE-QoS balancing strategy.

### 12.5.4 $\xi$-process-based scalable learning scheme

In Chapter 9, a scalable learning strategy based on stochastic process, $\xi$ process, is proposed and applied to feature learning using the dispersed knowledge-based systems [352]. To test the performance of the system with different methods, Standard AT&T(ORL) face database is used as a dataset, and a comparative analysis is performed among the methods, including Eigen feature extraction [51], fisher feature extraction [677], direct LDA (DLDA) [661],PCA+LDA [159], kernel PCA (KPCA) [527], and the proposed D$\xi$P-PCA strategy. For goal-based evaluation, the results of the given case study show that the proposed scalable learning strategy successfully performs the feature learning in a dispersed knowledge base, and the PCA based knowledge system with the proposed $\xi$ process is feasible to implement as a solution for face recognition.

As for process-based evaluation, the theoretical analysis involved in $\xi$ equivalency of the process shows that feature learning in a dispersed knowledge base with the $\xi$ process can be equivalent to a feature learning process in an integral database. The $\xi$ convergence analysis shows that the proposed D$\xi$P strategy guarantees a stable convergence to the optimal solution. Outcomes-based evaluations are given with criteria on recognition accuracy and time consumption.

The test shows that after collecting enough samples, the recognition rate of D$\xi$PPCA increases and gradually catches up with the other methods. With the proposed D$\xi$P strategy, even feature learning with a basic PCA computing archive achieves performance in recognition rate that is close to KPCA. As for time consumption, the time for training (TT) and recognition (RT) of D$\xi$P-PCA remains stable at about 10 sec and 0.9 sec, respectively. Compared with other methods, the D$\xi$P-PCA consumes more time in recognition because of the dispersed structure of the system, but less time in training, which is almost 1% of KPCA, 10% of PCA+LDA, 20% of DLDA and Fisherface, 24% of Eigenface. This case study shows that scalable learning with the $\xi$ process can save time in training and enable the distributed knowledge system to work as a centralised system while dealing with the scalable access without re-learning the whole data act.

### 12.5.5 Chaotic PKC-Based Confidential Communication

In Chapter 10, a chaotic public key cryptography-based confidential communication system is designed and applied to guarantee data security and privacy for the communication in the network [353]. With the combination of the PKC confidential communication and chaotic ciphering technology, a data-aware masquerading detection solution is also proposed. A comparison is drawn between the triple DES (3DES) [122] and the proposed method, as a proof of concept.

For goal-based evaluation, the tests show that the proposed method successfully protects the data using ciphering and masquerading attack detection. As for the process-based evaluation, the system in the proposed scheme is robust, with large key space against a brute force attack, hash-based embedded identification against a hill-climbing attack, and PKC-based malicious behaviour detection against a plaintext attack with masquerading nodes. Outcomes-based evaluations are given with criteria to analyse the correlation of the plaintext and encryptions, including correlation coefficient analysis of the pairs of pixels horizontally adjacent (HA) $R(x; x+1)$, vertically adjacent (VA) $R(y; y+1)$, diagonally adjacent (DA) $R(x+1; y+1)$, and overall correlation $\|R\|_n$. The quantitative evaluation shows that the proposed method has the lowest correlation coefficients and the overall $\|R\|_n$ is only about 16% of 3DES and 0.5% of the original plaintext. According to the results of qualitative analysis based on observation and process evaluation and quantitative analysis based on the outcomes-based evaluation, the proposed method provides a solution not only for the protection of the system ,but also for the detection of the attack.

## 12.6 Future Works

There are three main directions to improve the iHCI framework for mixed reality system, including fusion of computing awareness, sensing psycho-physiological signals, and ambient HCI in a wide area mixed reality environment.

### 12.6.1 Fusion of Awareness

In this thesis, three primary categories of awareness have been introduced for the system design. These are target-awareness, self-awareness and context-awareness. Awareness can be used to help the machine to recognize the objects and users as well as the scenario. Chapter 10 has presented a data-aware computing scheme for self-reflection and detection of anomalousness in the system.

Chapter 8 has presented a computational scheme for user experience modeling and processing. Chapter 5 to Chapter 7 have provided solutions for target-scene differentiation.

There are many factors, such as scenario, tasks, system condition of operation, user-experience, user behavior and motion, that would influence the performance of iHCI. If a system needs to take all those factors into account to perform decision-making, then a higher level of computational awareness may be necessary to facilitate the decision process. In some cases, various types of computational awareness need to be fused to complete such complex processing. Therefore, processing only one type of awareness is insufficient.

Even though pattern recognition and context-aware computing methods proposed in Chapter 7 have provided some references for context fusion, the relationships between various types of awareness are still unknown. Some types of awareness might be independent, some correlated, some overlapped, and some waiting for being discovered. To figure out the links between those categories of awareness and to build up a mechanism for fusion of awareness will promote the use of artificial intelligence in iHCI.

### 12.6.2 Psycho-Physiological Signals

Psycho-physiological signals, such as electromyography (EMG), electrocardiography (ECG), electroencephalogram (EEG), are also beneficial to the process and build up a higher level of user awareness. By recording muscle movements from EMG, heart beats from ECG and brain activity from EEG, more dynamical changes related to emotion and consciousness can be captured. With the support of expert systems, a computer can analyze and model these signals. Using expertise(professional knowledge), it is possible to strengthen the functionality regarding the awareness of the user. In Chapter 5 to Chapter 7, the work related to knowledge systems can be used to help transfer human knowledge into the computational system. Thus, the uncertainty of the knowledge and experience can be dealt with an adaptive learning process. Chapter 9 also provides a reference for the design of a knowledge system to make the knowledge scalable and accessible using a distributed structure. EMG, ECG, and EEG data are different from the vision data but can be converted into image data. Thus, related methods in this thesis can be applicable to psycho-physiology. Some modifications may need to facilitate the process.

### 12.6.3 Ambient HCI in Wide Area Mixed Reality

Most of the examples of ambient intelligence were implemented in a small room. However, when it comes to the wide area applications (e.g., military training), issues of system communication, data capturing, data processing, user positioning, resources allocation, sensor deployment, networking, etc., will challenge ambient HCI and the mixed reality system.

Positioning, and remote interaction are two main points for exploring the solution, . Positioning is an important issue to assess the quality of the training. In some cases of device based simulation, and global positioning system (GPS) may not be applicable, especially when applied indoors. Therefore, distance measurement systems are used to implement positioning task for this type of simulation. However, there are limitations. For example, in training for a sneaking mission, the interactions related to discovery or concealment depend on the distance between the receivers and transmitters of the devices. In some cases, the device based systems could not simulate the real world situation since the physical measure (e.g. radio communication, electronic wave) for transmitter and receiver do not correspond to the real world sensory (vision, illumination). Even if this measure could simulate the real situation, it has physical limitations. For instance, one should use a use depth map to compute the distance with depth information, whereas, devices with depth maps have a distance limitation such as 5-10 meters. However, the available distance of human vision (further than 50-100 meters) is approximately ten times as big as to the depth detectors. Meanwhile, in the real world, this type of interaction is not only related to the distance but also the appearance of the subjects. Therefore, when designing this type of systems. One must consider both the limitation of measurement and detection for simulating an immersive training experience.

To deal with this issue, Chapter 5 to 7 provide a reference for visual computing and target awareness. Chapter 8 and Chapter 10 provides references to design sensor networks and confidential communication. In this kind of application, some equipment (e.g. weapon simulator) with sensors are needed during the interaction. Thus, one of the main tasks in the research and development is how to combine the sensor equipment and computer vision based system so that together they act as a network with information fusion processing.

Another issue is remote interaction. For example, a group of participants may be located in different places but want to have training together in the same virtual environment. To perform ambient HCI at different geographic places and locations but in the same virtual world is a manifest action of a wide area mixed reality system, which is different from the interactions of an indoor virtual reality system. Although there were many examples related to the issues of ambient intelligence, networking, and communication in a virtual reality environment, the issues about the remote implementation of ambient interaction have not been addressed largely in mixed reality system. Meanwhile, when it comes to the question of a networked data system, the issue of distributed knowledge management may stand out as a constraint in the implementation of the system. Chapter 9 can provide a reference to the design and evaluation of a dispersed knowledge system design. However, related issues, such as communication coordination, remote operations, collaborative interaction and motion sickness have to be studied. GPS systems and Location Based Services (LBS) can be introduced for the implementation.

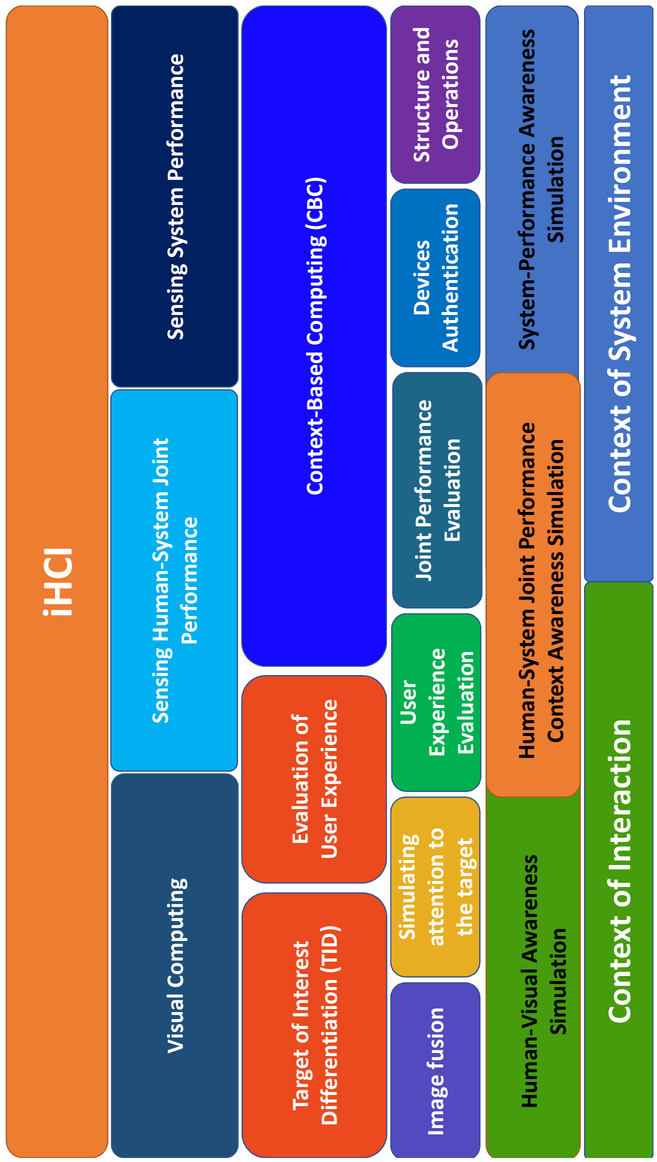


Figure 12.1: The framework of iHCI

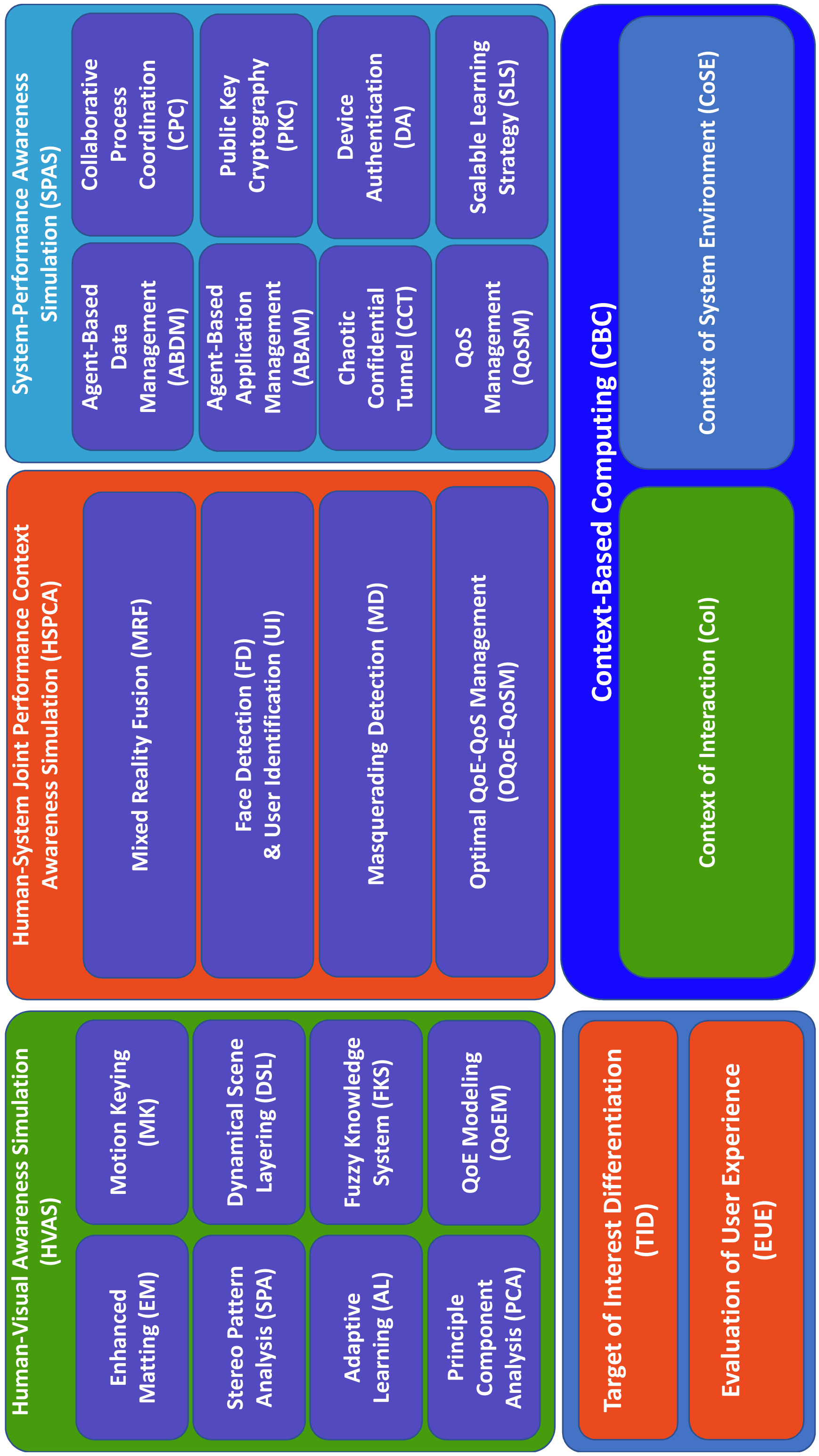


Figure 12.2: The main modules in the iHCI system

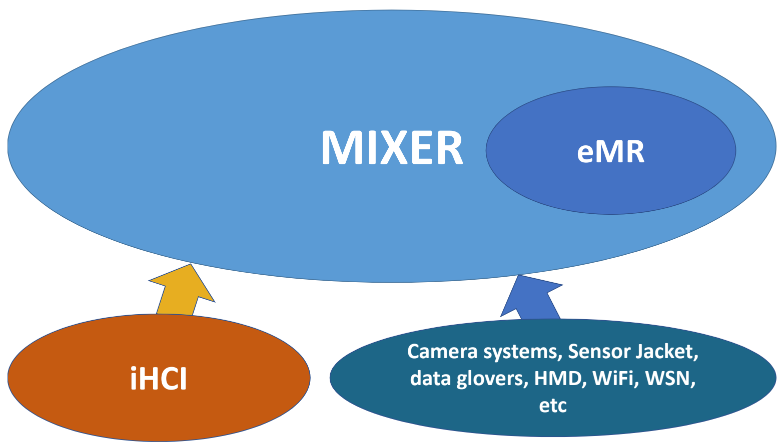


Figure 12.3: The relations between iHCI, MIXER and eMR

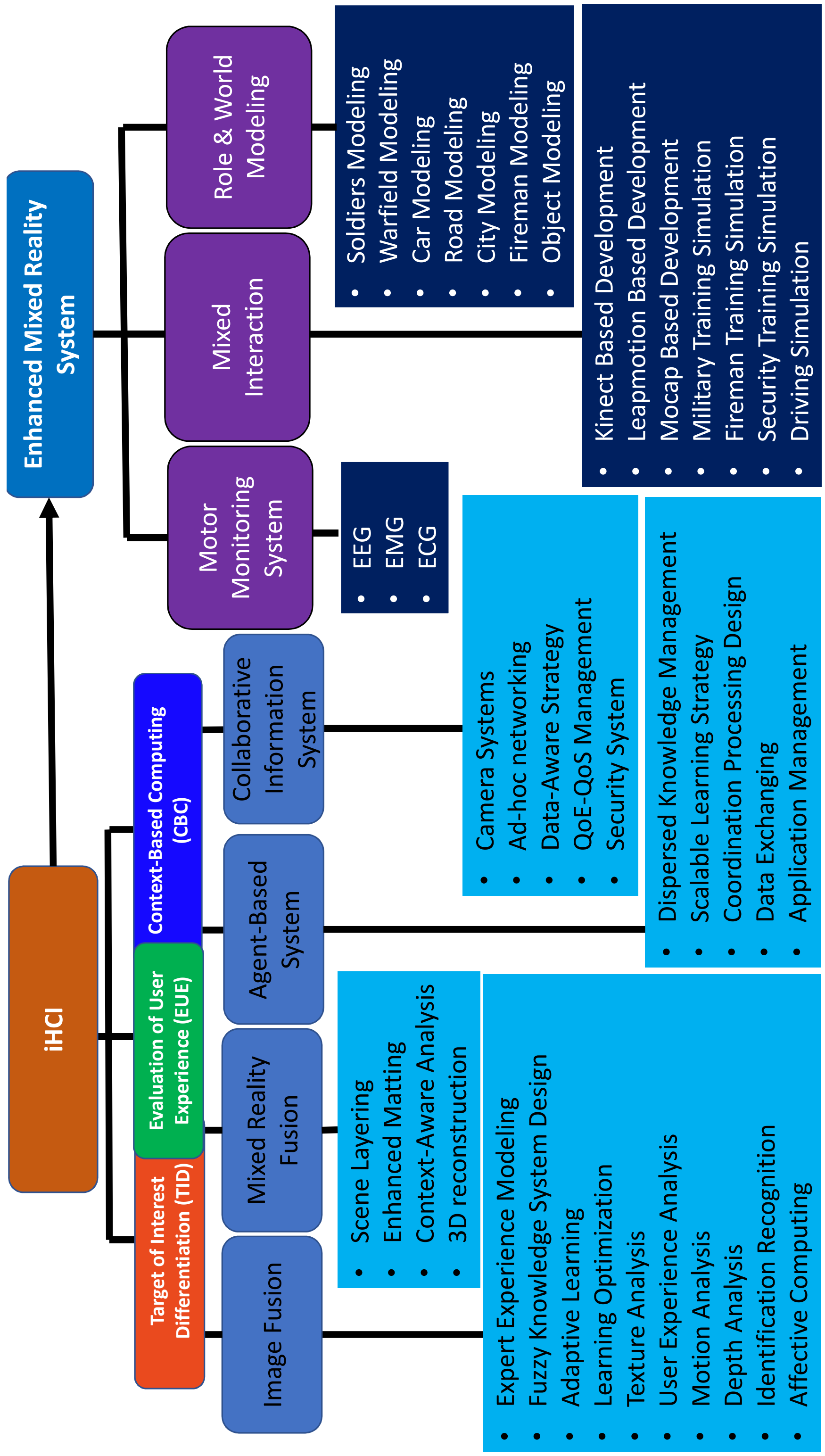


Figure 12.4: The functional structure of iHCI and eMR

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