AN EXPERIMENTAL RIG TO STUDY FLUID STRUCTURE FLOW INTERACTIONS IN BIOLOGICAL FLOWS

Ahmed Aldhafeeri

Bachelor of Engineering
Mechanical Engineering

MACQUARIE
University
SYDNEY·AUSTRALIA

Department of Mechanical Engineering
Macquarie University

November 06, 2017

Supervisor: Dr. Shaokoon Cheng

ACKNOWLEDGMENTS

I would like to thank Dr. Shaokoon Cheng for the advice, encouragement and patient guidance he has given me during my studies. I really think that I am so lucky to have you supporting me and my work. You have been always kind to me and always on my side, Also, thank you again because you gave me the opportunity to work in this field earlier during my bachelor. I really now think that I should extend my studies to a higher degree. I wish you all the best in your life and I hope that I will never let you down. Also, I would like to thank Mr. Joel Raco for the instructions he gave me during the semester I really appreciate your kindness and I wish you all the best for your future.

Your Student,

Ahmed

STATEMENT OF CANDIDATE

I, Ahmed Aldhafeeri, declare that this report, submitted as part of the requirement for the award of Bachelor of Engineering in the Department of Mechanical Engineering, Macquarie University, is entirely my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualification or assessment an any academic institution.

Student's Name: Ahmed Aldhafeeri

Student's Signature:

Date: November 06, 2017

ABSTRACT

The design is surely a talent in the engineering field and every day it is developing more. Designing an experimental rig to test different human non-rigid body models is kind of new idea to have more accurate results. Here, we design an experimental rig to test the flow structure interactions for several models. In this project, we want to make sure that the complete rig is able to run different models. Design the experiments including the components we need to attach to it is the aim of this thesis. Linear actuator system will be designed for this rig and will be programmed to act on the model to apply a dynamic wall motion on the model. Also, designing molds and cast models is part of this thesis and many techniques will be used to achieve that. In the following chapters, each part of the required tasks will be explained in details.

Contents

List of Figures

Chapter 1

Introduction

In one way or another everyone has attempted to fix a problem and get things back to track an illustration that everyone has at a point in time in his lifetime been a mechanic before [1]. Mechanics revolves around the study of how structures and systems of biological organisms, ranging from the smallest plants to the largest animals, respond to different forces and stimuli from the external environment. In the human aspect, biomechanics deals with the study of how the musculature and skeletal systems function under various conditions. Mechanics generally, therefore, defines how scientists attempt to apply physics besides other forms of analyses that are based on mathematics to realize the capabilities and limits of biological systems.

Mechanics is traced back to the times when the aggressive Greeks and Romans dissected animals and vivisected human beings so as to establish the composition and functioning of the inner body systems [10]. Philosophers and scientists of the ancient times also gave a hand in the development and promotion of elements of mechanics. Mechanics of the galloping motion of a horse took interest in the 19th century when a number of Europeans found fascination in the gait of horses. Currently, more than just a field where philosophers and scientists meet, mechanics has an own branch of human and biological science.

1.1 Project Goal

The goal of this project is to design experimental rig which is able to test different models. Design the experiment and manufacturing have been completed and setup the experiment is ready. The meeting is a must to make this project successful and scheduled weekly meeting have been arranged during the semester to make sure the progress of the project is going well. Linear actuators will be used to design a system that will be able to apply dynamic motion to the model's wall during the experiment. One of the requirement to complete this project is to design and program linear actuators system for the experiment and more details about this part will be explained clearly in Chapter 3 $ 4. Fabrication and casting are taking a huge part in this project. For example, the scaffold is necessary to hold the model while pumping the fluid to make sure the model will remain stable while the experiment is on. So, this thesis is aiming to design an experimental rig with the required system and components needed to run the experiment.

Chapter 2

Background and Related work overview

2.1 Human Upper Airway (HUA)

2.1.1 Introduction

The Human Upper Airways system is a multifunctional, complicated and ever changing neuromechanical system and its patency require a coordination which is time-to-time of the mechanical and neural behavior that is a factor of the posture [3]. The human upper airway is an everchanging structure which permits speech, swallowing and respiratory functions. It mechanical behavior and neural control is determined by the evolutionary compromise between these functions hence the system tends to respond rapidly and in a way that is controlled dynamically. There are variations that are experienced in the system during the respiratory cycle which ranges from being awake and asleep and between the stages of sleep.

Apneas or hypopneas are a condition that may result from failure of continuous coordination and recruitment of the dilator muscles that are responsible for the counterbalancing of the forces acting to close the airway. An alteration of the passive mechanical behavior of the upper airway may result in its collapse. Such alterations or variations can be due to obesity or variations in the anatomy for example retrognathia. This behavior is a factor of the mechanical behavior of each of the tissues of the mechanical airway in isolation, their physiological interactions as well as their geometric arrangements. The respiratory cycle experiences the different movement of the soft tissue as illustrated by measurements of deformations related to respiration. It is not possible to predict the biomechanical behavior of the human upper airway just from the electromyography activities of its muscles [4].

2.1.2 Mechanical Models of the Human Upper Airway

The pharynx is in most cases thought to be a floppy tube. Mechanical models of collapsible tubes including Starling resistor are used in relating intraluminal pressure, perypharyngeal pressure as well as airflow [5]. These relations have provided a basis for the analysis of limitations of flow mechanism when takes place when the rising negative pressure in the epiglottis does not manage to control airflow and how collapse can be encouraged by additional peripharyngeal tissue. The patency of the upper airway has been perceived and understood to be dependent on a balance between activities of the muscles and the pressure of the airway as conceptualized by Isono and the colleagues. This group conceptualized that the airway was balancing on a pivot which represents the intrinsic behavior of the upper airway. Another conceptual model by the same group was involving a balance between intramandibular volume and the soft tissue that gave an explanation on how the posture of the head, jaw, and neck and obesity are able to lower the volume of the oral cavity and the pharynx [6].

The response of the upper airway tissue to a deformation or applied load defines its passive stiffness and is normalized by the area over which the load is applied. This is similar to the modulus of elasticity concept, commonly referred to as Young's modulus which is an expression of the force acting per unit area divided by strain i.e. change in length per unit area. The modulus of elasticity in the upper airways is a factor of the rate of loading, the quantity of load applied and the direction of application of the load. An increase in the load quantity increases the modulus of elasticity and is usually a nonlinear elasticity [9]. This means that in case any of the upper airways tissues are slack or tend to be slack then small pressure variations culminate into enormous deformation of the walls of the airways.

Under constant conditions of pressure and force, the tissues are likely to deform over time. On the other hand, application of a constant stretch decreases the tension over time making the tissues to relax even though there is usually a residual stress that is left in the tissue. Tissues tend to be stiffer when the rate of application of the load is higher. These characteristics define the viscoelasticity of the soft tissues of the upper airway. Important to note as well is that muscles are normally stiffer in the direction of the fascicles of the muscles as opposed to perpendicular to them [2]. This means loads applied in varied anatomical directions end up in different movements. The biochemical responses of the upper airway are influenced by the geometric or anatomical characteristics of the airway. This has been used in explaining the reason for increases OSA rates in males since they have longer pharynx as compared to their female counterparts. This is influenced by two factors. The airway surface area tends to be larger in a longer structure thereby air pressure is applied over a larger area and thus greater force is produced. Another reason is that a longer structure is found to be significantly more flexible than a shorter structure with similar cross section [8].

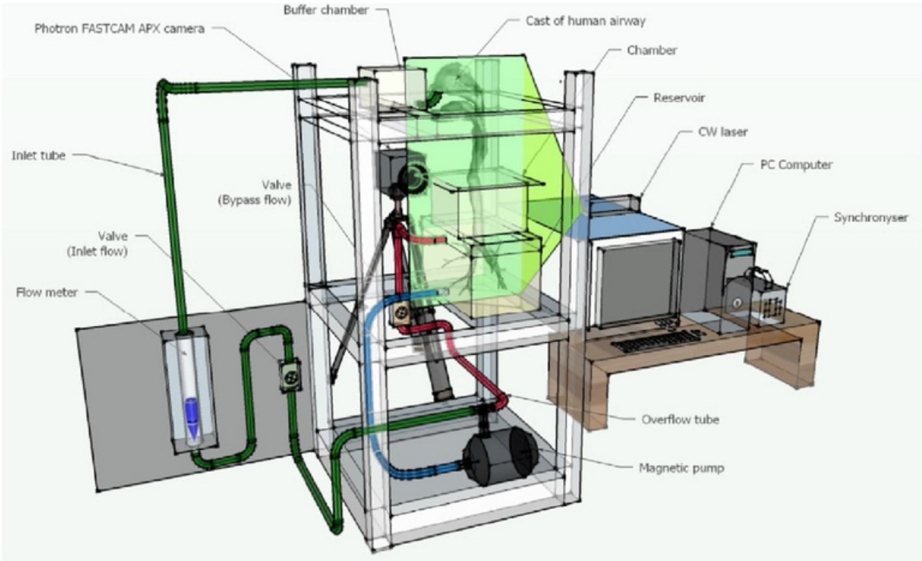


Figure 2.1: Sketch of the experimental PIV apparatus from a previous research [13].

2.2 Arduino

2.2.1 Adaptability

The Arduino is making life easier because of its adaptability and ease to be used in various projects since the codes can be fed into the Arduino from an external source which means that an Arduino can be used for various purposes and electronic projects. The Arduino can interact with buttons, speakers, GPS units, the internet and even a smartphone which makes them very adaptable for use in programming. There is growing used of the Arduino due to its compatibility with a smartphone which can be used to control as well as load codes to the Arduino. There is ease in access to a smartphone and internet which makes it easy to access codes that can be used to program an Arduino making it more efficient and an effective circuit board for a small scale electronic project [18].

The Arduino is a microcontroller which makes it easy to work with as well as allow easy and first prototyping. This feature has increasingly improved the use of the Arduino in the programming of basic electronic projects. However, the ease of understanding and operating an Arduino makes it more preferred by many developers who need to create their product prototype with time. The Arduino has proved to be powerful and convenient for all users with different specifications. The Arduino provides the users with significant simplicity compared to other programming circuit boards because it is easily compatible with an LCD screen or a smartphone to display messages within the shortest possible time. The Arduino allows the electronic developers to manipulate the microcontroller for more control and optimization by creating more codes which can be fed to the microcontroller through the USB cable. The Arduino comes already with a complete platform which does not require the developer to create codes or wiring. The prewired and coded nature of the Arduino makes it easy to use and adopt especially for prototypes which require immense testing. The Arduino ensures that developers can concentrate on the testing their ideas using the already existent free codes in the Arduino library. Therefore, the ready to use the structure of the Arduino makes it more easy to use and the most preferred programming circuit board by the developers [19].

2.2.2 Effortless function and large community

The Arduino is easy to use and easily adaptable with less technical knowledge which increases the high preference from developers to use the Arduino. The Arduino has many functions which are evident in the device-wide software which is easy to manipulate and create codes fast which is not possible when using other microcontrollers which require complex procedures to write new codes and instructions making it difficult to customize their control [20]. The Arduino has a large community of users who are already using the microcontroller and are aware of how to solve the microcontroller problems making help and advice on its use easily and widely available. The large community using the Arduino makes it easy for new users who can get the microcontroller best practices and approaches to control from the users online at any time [21].

2.2.3 The already set hardware of the Arduino

The Arduino hardware is already set and functional which is the reason behind the ease of use of the microcontroller. The Arduino with it's already in place hardware platform only require slight software modifications which can be done easily through the USB which allow easy programming and saves time for the user [22]. Setting up a hardware from scratch is expensive and time consuming compared to acquiring an already configured Arduino. Further, testing a microcontroller that has been created from scratch is time-consuming and can take more time which could be used in testing the prototype. The already set framework of the Arduino makes it easy for the developer or the third parties to create add-ons because the Arduino is already supported [23].

2.2.4 Cognitive load and start time of using the Arduino

The Arduino requires less input regarding its cognitive load and start time compared to other microcontrollers which need significant input regarding software hence, consuming a lot of time which could have been used in the development and advancement of the prototype. The Arduino has a spontaneous start after acquiring it which only requires connecting with the actuator. The working environment of the Arduino already has a crowd of fans and hobbyists who are ready to help the new users. The Arduino further has a library that enables the device users to connect the Arduino with a wide number of hardware. The Arduino is designed to provide the users with the easy debugging environment with a cross-platform that is accepted by a wide devices or hardware. Therefore, regarding speed and ease of development, the Arduino is very effective and efficient which makes it highly preferred [24].

All the parts we need to buy is so cheap because they are already assembled, and all that is needed is connecting the Actuator with the Arduino. The availability of an already complete system and framework makes it cheap to use the Arduino yet the results after the prototype testing is as good as the other high-end microcontrollers which are rigid to manipulate and use in a normal setting. Further, the ease of availability of parts needed increases the exponentially of the Arduino due to its readability as well as ease of use. The Arduino comes in complete package which includes the 5 volts regulator, the Oscillator, a serial communication interface, a microcontroller and headers for the connection to the actuator [25].

Chapter 3

The Experimental rig

3.1 Design The Tank

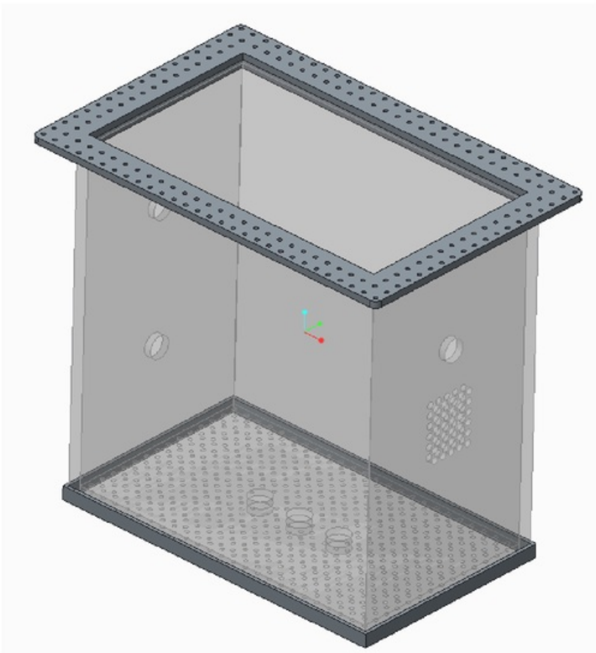


Figure 3.1: The experiment tank

The first step for this project was to design a tank that can test many different models. The tank has been designed and sent to a manufacturer to be manufactured. It has many components attached to it such as linear actuators system, pump, and hoses. This project is aimed to design the required components to make the rig ready.

The tank has many features which make it unique and can not be purchased from the market. So, the only option was left is to design it and manufacture it. One of the features it has is many holes method and this method is used in our case to make it easy to attach components to it and ensure the flexibility of position. The advantages we have from this tank are as the following:

- Big enough to contain the average size of different models that we will be testing.
- Enough space to work with your hands in it to set-up the models and fix the position.
- The top piece is having a pattern of holes to make sure that we can change the position of the actuators with respect to the model geometry.
- Two holes on the left side of the tank as a hoses inlets. This to make sure the flexibility of the hoses is perfect because we do not want to bend the hose. Bending the hose will affect the velocity of the fluid also many other characteristics. So, it is always good to have it in straight line position.
- On the other side of the tank, we have an outlet and grid holes pattern for the actuator. The holes are to make sure that we can change the actuator position with respect to the model geometry.
- In the bottom base of the tank, we have three inlets to make sure that we can have an inlet suitable for each model case we need to attach to the tank.
- At the bottom, we have holes pattern to make sure that we can mount components in the tank.

More details on the features and the components will be discussed in the following sub-headings.

3.2 The Experiment components

3.2.1 Tank

Figure 3.2: The experiment tank

As it can be seen from the figure above that this tank will be using as the main part of the experimental rig. Also, Figure 3.2 shows that the tank has been manufactured successfully and it is ready to be used. As discussed earlier the tank have many features that can be useful in the future such as multiple inlets and outlets. Also, the space inside the tank has been considered to be enough to do work inside the tank by hands. For example, fixing the model position and mounting scaffolds. The tank has been made from Glass and acrylic with aluminium braces to make a clear spot for the camera to take the results clearly during the experiment. The tank is not heavy and this is an advantage for it so it can be easily moved from place to place. For the full assembled rig the tank will be placed on a trolly.

3.2.2 Actuators System

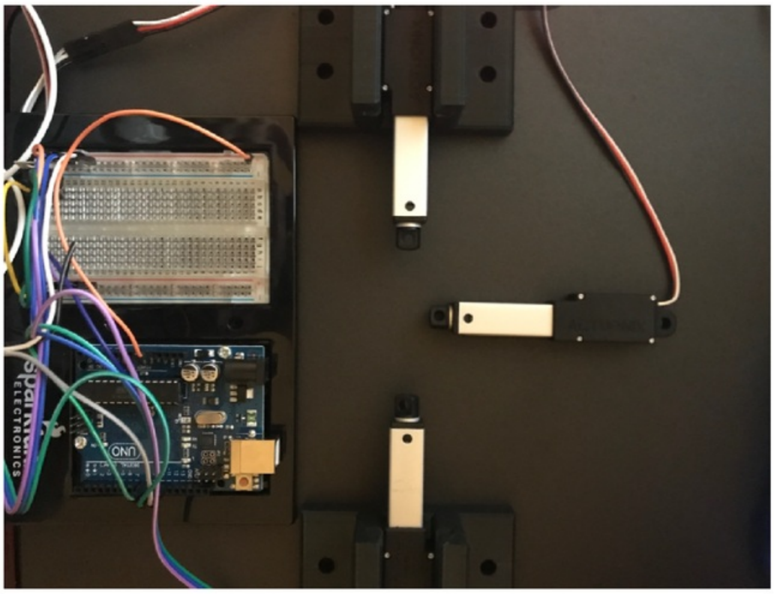


Figure 3.3: Linear Actuator system

The Linear actuator system is the most important part of the experiment. The system is designed to be able to apply forces on the model wall to create wall motion. As figure 3.3 shows, the system has been designed and programmed successfully and ready to be mount to the tank. The system has been programmed using Adruino Uno micro-controller which is the best way to control this type of actuators as it is mentioned on the manufacturer website. Since Arduino is the best way to control this type of actuators it was very efficient to program the actuators. The breadboard has been used to build the electrical circuit and to power the actuators.

Power

The power supply is necessary to power this system and it should be enough to power the 3 actuators equally. A 9V DC power supply has been used to power the system in figure 3.3 with 1.67V for each actuator. Each Actuator can take a maximum of 6V and a voltage regulator was used to ensure that only 5V can flow through the whole system. As a voltage regulator, 5V 1.5A Linear Voltage Regulator - 7805 TO-220 has been used to regulate 5V of the power supply.

3.2.3 Pump

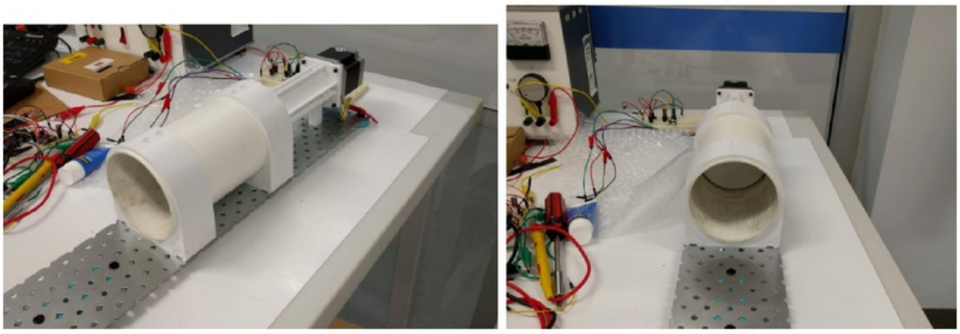


Figure 3.4: The pump will be used in the experiment.

This section has been added to make sure that all the components of the experiment are explained clearly. The pump is part of the experiment and it was successfully designed and programmed by Mr. Joel Raco. Mr. Joel Raco was responsible for the pump design and programming to be able to control the fluid flow as a sine wave function. The pump is able to have a full control over the flow velocity. The pump job is to have a stable flow through the model during the experiment from a reservoir which is also attached to the tank. The fluid has particles so in future studies the Particle Image Velocimetry (PIV) Measurement Systems laser can detect these particles to get the results of the flow velocity.
[1]

Pump extention

Figure 3.4 shows the pump extension which contains pipes and hoses attached together to make a flexible extension that will be attached to the pump and the tank. With this extension, the flow will be able to flow from the pump through the extension then the model. The extension has been tested in water to make sure that there are no leaks that might affect the flow of the experiment.

[1] *NOTE: The pump and the extension in figure 3.4 and 3.5 has been made by MR. Joel Raco MRes student at macquarie university.*

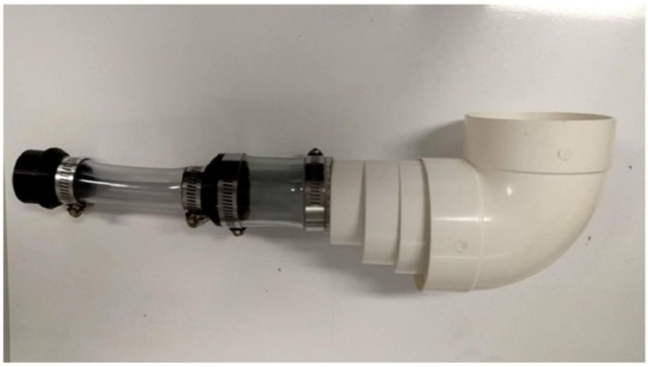


Figure 3.5: Pump extension

3.3 Silicone Rubber Model

[2]

Figure 3.6: The silicone model used to test the experiment.

As figure 3.6 shows the silicone rubber models that have been used to test the actuators system. It was a successful attempt were the actuators are able to apply enough dynamic force to act on the model. These results are important to make sure that the actuators system is working very well. At present, the actuators we have are not the best choice that can fit all the different model as every model has different thickness and geometry that might need more force that can push the wall. some considerations that have been taken into account that the fluid travels through the model requires more force from the

[2] *NOTE: The pump and the extension in figure 3.4 and 3.5 has been made by MR. Joel Raco MRes student at macquarie university.*

actuators system. The cast of these models is has been done successfully and it is ready to be fixed in the tank and test it.

Chapter 4

Linear Actuators System

4.1 Actuators

4.1.1 Introduction

The Linear actuator is a device that enables building displacement and linear motion which is characterized by a straight line. This type of actuator operates contrary to the conventional electric actuator which facilitates building up of circular motion. The Linear actuator which is also referred to as linear motor is mostly used in situations whereby the need for a machine to shift loads is required. Industrial Machinery and machine tools, computer peripherals use linear actuators since they require linear motion in their operations. The Linear motion being an essential aspect of every machine or tools, demands the use of this type of actuator since it facilitates operations such as lifting loads in a manufacturing organization. Linear actuators are the most effective as compared to electric kind since it builds up enough force which is necessary for performing some duties using industrial machinery [12]. There are varieties of the linear actuator in the market which includes; the mechanical actuator, the hydraulic actuator, piezoelectric actuators and electro-mechanical actuators. These types of linear actuator are differentiated by the process which is experienced to enable linear production motion. The mechanisms employed by an operator in the production of linear motion also posts variations between these actuators. The electro-mechanical actuator operates similarly to the mechanical actuator [12]. The slight difference between these actuators is that electro-mechanical has an electric motor which functions the same as the control knob in the mechanical actuator.

4.1.2 Efficiency

Linear actuators are of great importance to organizations since they facilitate accomplishment of various central activities. Designing and assembling linear actuators is among the best and appropriate ideas which can be considered as it is financially beneficial. Purchasing the actuators from the market is also an option which can be considered since they are easily accessible in various retail and wholesale outlets. Efficiency is a central issue which moderates the decision to design or buy linear actuators from the market. This issue is characterized by time consumption and ability to achieve great results in the intended timeframe. Linear actuators are industrially manufactured devices whose production is guided by various standards [12]. The designing option is not efficient since it requires an organization to observe a lot of manufacturing standards. Standardization of the actuators guarantees their potential to perform appropriately and durability too. Designing linear actuators can lead to the production of substandard devices which does not guarantee an organization perfect performance of the intended use. This aspect portrays that, purchasing actuators from the market since it is easy to access quality and standard ones in the shortest time. The availability of variety based on quality and durability guarantees an organization of the actuators' efficiency. The efficiency of a machine is the primary consideration which guides customer decision to purchase and what makes the option to buy linear actuators from the market the best and fantastic option. Designing them may seem less costly, but it may result in high depreciation rate since there is no guarantee of their durability.

4.1.3 Buying the actuators

Buying linear actuators from the market is the best option since it does not require adherence to manufacturing and assembling requirements as compared to in-house designing process. Designing actuators require an individual to gather base, gateway, aluminum extrusions and drive units. It also requires recruitment or hiring linear motion and control expertise which is a highly demanding process. Buying the actuators from the market enables an individual to access industrially standardized devices which meet their customer needs. The expenses incurred while implementing the manufacturing and assembling requirements are not experienced during the purchasing process of linear actuators from the market [14]. These requirements are implemented by manufacturers of the actuators in the market hence making it easy for individuals buying them not to consider such aspects of the decision making process. This aspect reflects the validity and suitability of buying the actuators from the market as opposed to designing them since it does not incorporate the implementation of manufacturing and assembling requirements.

4.2 Programming

Linear actuators should be programmed to enhance effectiveness, capacity, and speed using Arduino. Arduino is software and hardware device which is used in controlling large linear actuators and expansion of their capacity too. Programming linear actuators using Arduino involves various steps which are; wiring the board basics, programming the board basics, the creation of H bridge between relays and interfacing with the motor controller [15].

4.2.1 Arduino

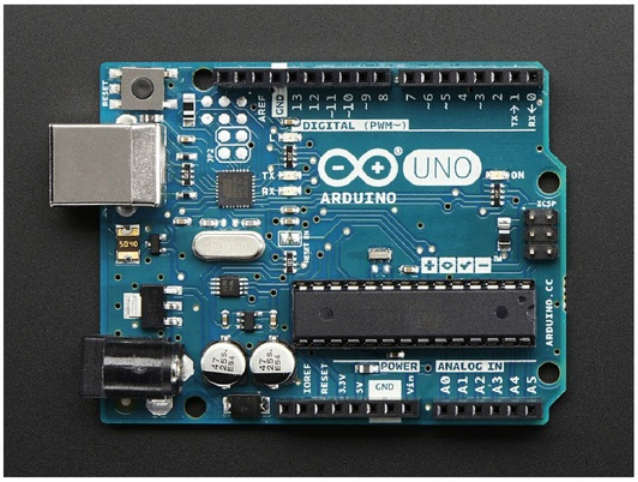


Figure 4.1: Arduino UNO

Introduction

An Arduino refers to an open-source computer that is used in major electronics projects; an Arduino has both the physical circuit board which is programmable and a software referred to as the integrated development environment which runs on a computer system and it is used to write and upload programmable codes to the physical board which is used to provide function instructions to the operations of the Arduino. The Arduino is a programmable circuit board that is easy to use and assembles which has made it popular with people starting out in electronics prefer to use the Arduino circuit board. Unlike the other types of the circuit boards that can be used in assembling electronics, the Arduino does not need a separate piece of hardware also known as a programmer which is used to load new code or instructions to the circuit board [16]. In the case of an Arduino, one can use a USB cable to load codes to the device which makes it more dynamic and adaptable. The Arduino provides a standard factor that can delegate the functions of the microcontroller into a more accessible device for diverse programming. The Arduino is also a perfect circuit board for basic electronic projects because of its ease of use and adaptability. The USB cable used to load codes to the device is also used to connect the Arduino to a power source. The Arduino will be effective in programming the linear actuator because of its simplicity as well as its ability to create interactive environments. The flexibility of the Arduino and its availability ease makes the Arduino circuit board the best device to program the actuator [17].

4.3 Coding and programming

Coding the is the main part to programme the Arduino board to be able to perform as required. Since the Arduino is using C/C++ as a coding language it is not that complicated language to use for programming the system. The code for the actuators system is not very simple since the system require the code to be able to control the velocity by using a sine wave function. In order to do that, the sine function has been made in the code using a timer-r1 Library in Arduino. The sine wave function is as the following:

$$v = Asin(Bt + C) + D \tag{4.1}$$

Where,

- v is the velocity function.
- A is the amplitude in our case Max velocity.
- B is related to the period of oscillation.

$$T = 2\pi/B \tag{4.2}$$

- C is constant x offset.
- D is constant y offset.

These variables above is implemented to the code and after doing that we have full control over the velocity function. The code in the appendix is the full code that controls the actuators system as a sine wave function.

Chapter 5

Fabrication and Casting Models

5.1 Scaffold

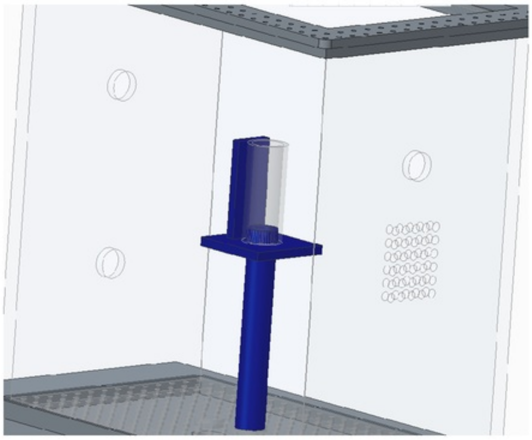


Figure 5.1: Actuator mount assembly

The scaffold is designed to be able to hold the model inside the tank so we make sure it is not moving while the experiment is operating. If the scaffold is not well designed then this may be affecting the results. There are many ways to design and manufacture the scaffold, research has been made to make sure that we get the best ways to manufacture the required quality in most inexpensive case. CREO Parametric 2.0 has been used to design the parts required to hold the model. As an engineering student at Macquarie University, it was the best option to work with. As a CAD software, it has many features which was very useful and fast while designing the parts.

5.1.1 3D Printing

Actuators mounts

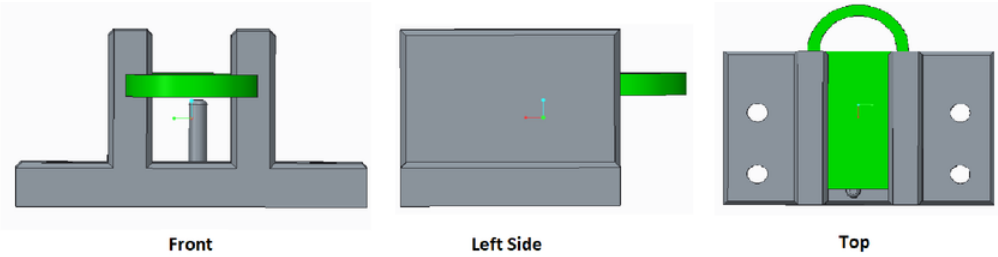


Figure 5.2: Actuator mount assembly

As it can be seen from figure 5.2 above the mounts are designed to hold the actuators on top of the tank. These mounts are perfect for the actuators because they ensure that the actuators will not move in x,y and z-direction while performing the experiment. To achieve the most stability a pin which is shown clearly in figure 5.1 front view that will fit in the actuator backside. The grey part of the figure is the mount itself and the green part is a key to hold the actuator from moving in the z-direction. These mounts are 3D printed using SLA filament which is solid enough to hold the actuators during the experiment.

Actuators arms

The actuators will set on top of the tank which is filled with water and it will not be able to be placed inside the tank. 3d printed fabricated arms have been designed as an extension of the actuators to be able to produce the wall motion. These arms are designed to fit inside the tank to act on the model and several considerations have been taken into account to make this happen as the following:

- The distance from the actuators to the needed point on the model.
- As the arms are long, supports in the corners of the arms are needed to make sure there is no deflection of the arms during the experiment.
- The arms are well printed to make sure it fits the actuators to hold the position of the act.
- Use a solid material to print these arms as stereolithography (SLA) filament.

Moulding design

Moulding design is a very long process to make sure the cast well structured. Computer-Aided-Design (CAD) has been used to design the mold to cast the silicone rubber model successfully. The design is made to cast the model during a long process of 4 days for each cast. The molds are printed using polyvinyl alcohol (PVA) since this material is ideal in such a case. PVA is perfect since it can be dissolved in water in few hours. During the casting procedure after mixing the silicone it can be filled in the mold and wait for it to dry for several hours. After the silicone dry the cast will still have the inner part of it and needs to be dissolved. The way that has been used to do that is to place the cast in a cup water and wait for few hours to be fully dissolved.

The process of the cast has been conducted as the following:

- Design the mold using Computer-Aided-Design (CAD).
- print the mold using 3D-printer.
- Use polyvinyl alcohol (PVA) as a material to print the molds.
- Mix the silicone and place it in the vacuum chamber for few hours to be free from air bubbles.
- After the silicone mix is free of bubbles it is ready to be filled in the mold.
- After several hours (12-24 hours) the mold is ready to be de-molded.
- The silicone part will still have the inside part of the PVA material and needs to be placed inside a water cap to dissolve.

5.2 Silicone model

5.2.1 Method

In order to cast the silicone rubber model which is required to test the experimental rig is a long process. The silicone material is a result of a material mix that will end up forming silicone rubber with the required properties. The two materials are mixed with a ratio of 9:1 as it is mentioned in the silicone rubber spec sheet in appendix D. The procedure for this casting is depending on the casting volume and increases if the volume increased.

Figure 5.3: Human upper airway silicone rubber model

[1] To make sure that the cast is successful the cast should be free from air bubbles. To ensure that the cast is free from air bubbles a vacuum chamber has been used to free the silicone rubber mix from air bubbles during a specific time. As an early stage of this project silicone rubber model of the tube has been successfully cast to test the experimental rig and the actuators. This model has been made successfully after few attempts and free of air bubbles.

[1] *NOTE: The cast in figure 5.3 has been made by MR. Joel Raco MRes student at macquarie university.*

5.2.2 Casting procedure

Figure 5.4: Silicone mix materials

As it can be seen from the figure above that the material required is a mix of two different liquids. The two containers shown in figure 5.4 should be mixed in a ratio of 9:1 respectively to the figure. The volume of the required model should be calculated before mixing the silicone as it is required to mix it with the 9:1 ratio. This mix after it is filled in a separate cup each and the will be weighted to make sure it will be mixed with the required ratio. Figure 5.5 below on page 26 shows the device used to weight the materials during the casting procedure.

5.2.3 Weight measuring device

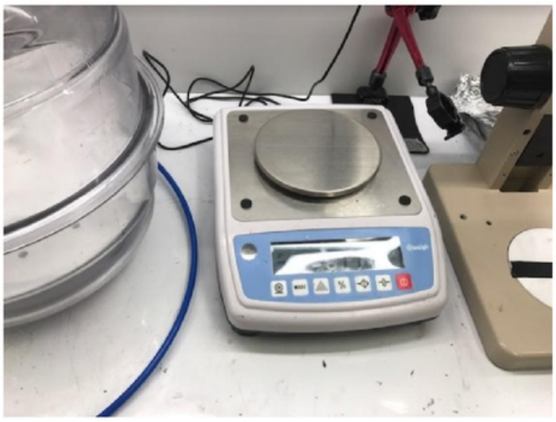


Figure 5.5: Weight measuring device

The figure above shows the device that has been used to measure the weight and get the volume to mix the silicone rubber material to cast the required models.

5.2.4 Vacuum Chamber

Figure 5.6: Vacuum Chamber used to free the silicone mix from air bubbles

Figure 5.6 shows the vacuum chamber device used during the casting procedure. After research and some experimental tests, this method was the best to use in such case. The device is able to contain the mix inside it and vacuum the air inside the mix in order to have bubble free mix before cast. The process for this method takes an average time of 1-2 hours for each cast and it depends on the volume of the cast. After the mix is free of bubbles it can be filled inside the mold which should be ready and well designed to avoid any leaks and air bubbles.

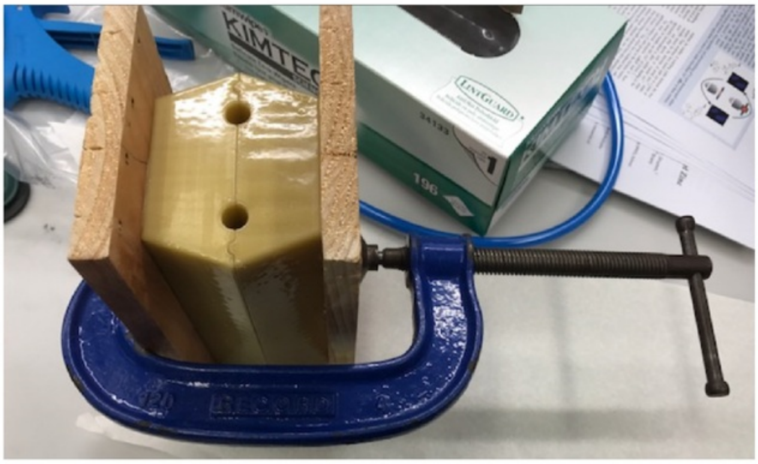


Figure 5.7: The polyvinyl alcohol (PVA) mould used to cast the silicone rubber model

As it can be seen from figure 5.7 the cast setup is ready to be filled with silicone and wait for it to dry. The mold has been made from polyvinyl alcohol (PVA) material which can be dissolved by placing it in water for few hours. Also, the figure shows how the mold setup is clamped to make sure that no leaks and air is entering the mold while the silicone is filling. The two holes on to of the mold are designed as a silicone inlet and air outlet. By using this method, the model should be free from air bubbles. The process is long and can take 4 days to cast one model and that including 3D-printing, mixing the silicone, molding, vacuum chamber and casting the model. The procedure for the full cast as the following:

- 3D-printing the designed mold.
- Smoothing the molds using steam chamber.
  - *Recommended for polyvinyl alcohol (PVA).*
- Mix the silicone rubber material with a ratio of 9:1 as discussed earlier.
- Place the mixed material in a vacuum chamber to suck the air to avoid air bubbles.
- Setup up the molds and clamp it to make sure that there is no leak and air bubbles enter the mold while filling the silicone material.

- Wait for the silicone to dry then de-mold the two mold to get the silicone model.
- dissolve the inner PVA part of the model by placing it in water.

Chapter 6

Results and Discussion

This thesis is aimed to design an experimental rig that can fit several different models to study Fluid-structure interaction (FSI) in biological flows. The tank has been designed successfully to be able to fit different model in it with respect to their dimension. The tank is able to fit the human upper airway (HUA) also the abdominal aortic aneurysm (AAA) model which they are the most cases they study using a similar experiment.

6.1 The Experiment Tank

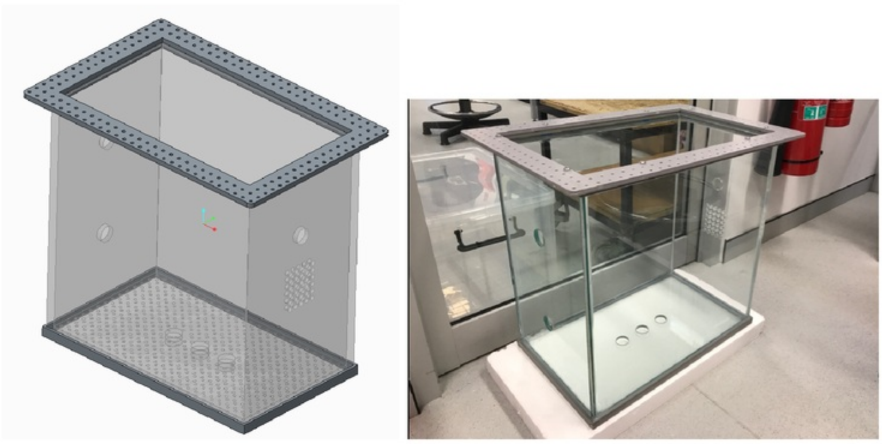


Figure 6.1: The experimental rig tank in CAD and after manufaturing.

As figure 6.1 shows that the tank has been designed and manufactured successfully and it is ready to be used for future experiments. The quality of the tank is perfect and has the exact dimensions as mentioned in the drawing included in the appendix. The tank does not required any development since it is designed to consider many different of models.

6.2 Linear Actuatiors System

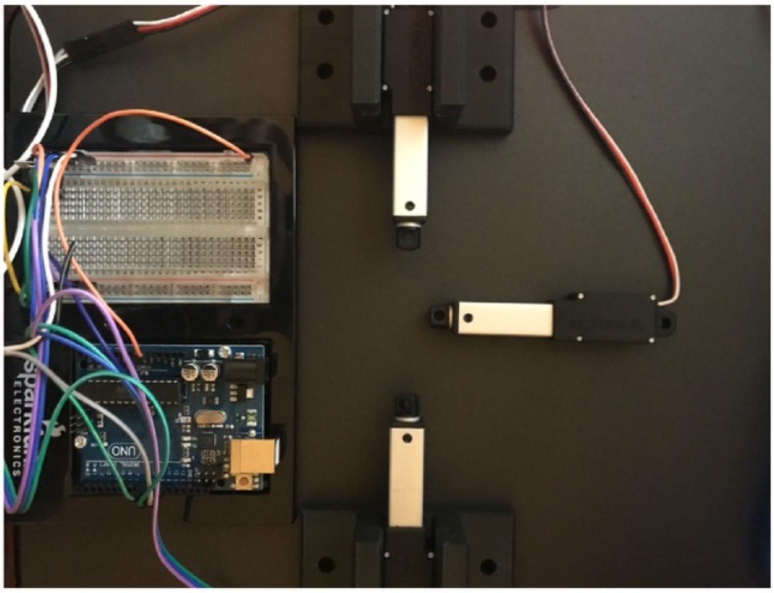


Figure 6.2: The Linear Actuatiors System

As it can be seen from figure 6.2 the linear actuators system has been made successfully and it is ready to use for the experiment. However, this system requires improvement for the future studies. The improvement is including the actuators size and type and any other specifications that the study required to meet the requirements of the experiment. The force generated by these actuators is enough to simulate the silicone tube model with a thickness of 5mm. A sine wave function has been integrated into the Arduino code successfully and by using the code we have full control over the velocity function. The function we have is the following formula :

$$v = Asin(Bt + C) + D \tag{6.1}$$

Where,

- v is the velocity function.
- A is the amplitude in our case Max velocity.
- B is related to the period of oscillation.

$$T = 2\pi/B \tag{6.2}$$

- C is constant x offset.
- D is constant y offset.

6.3 Silicone tube mould and cast

Figure 6.3: The Silicone tube mold

As figure 6.3 shows the mold used to cast a silicone rubber tube model to test the actuators system, It was a successful attempt for the actuators that they were able to push the wall of the model as required. The cast of this model is a long progress as discussed in chapter 3. The model has been made as required with good quaility after 2 attempts. The 3D-printing tachnique and the PVA material were ideal solutions to cast this type of model.

6.4 Full Experiment

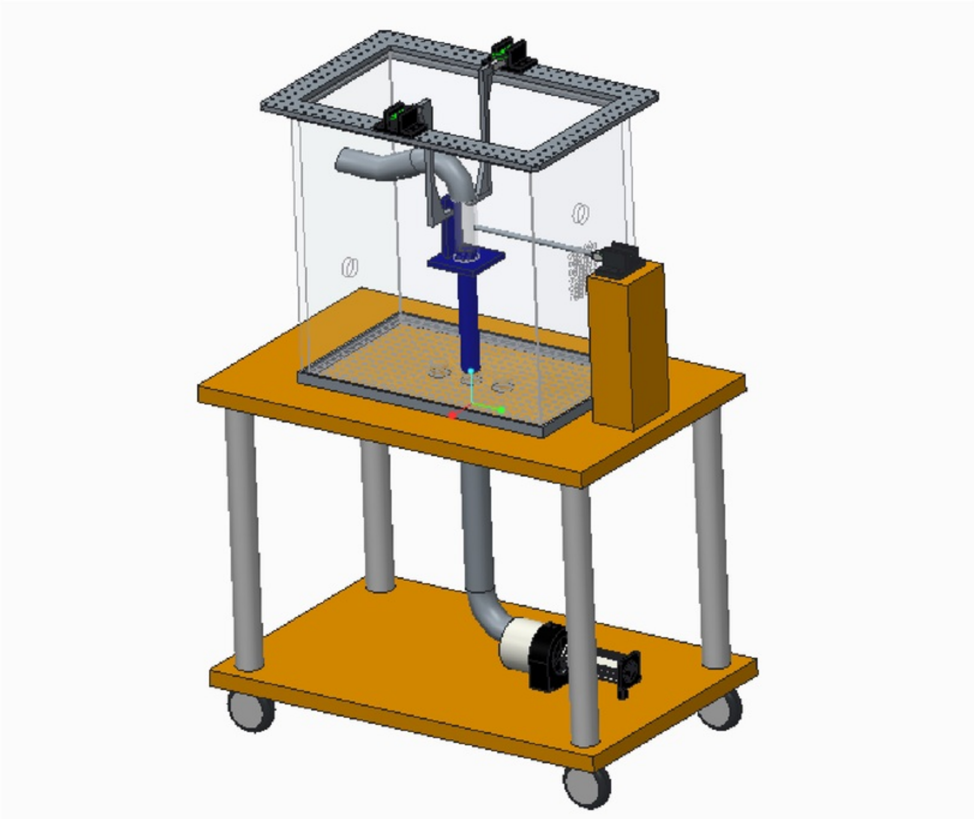


Figure 6.4: The Silicone tube mold

Figure 6.4 shows the final rig assembly in this thesis. The assembly has all the components attached to the tank to be ready for testing the models. The rig is placed on the trolly that will make it easier to move from place to another. Also, hoses are attached from the model to the pump and the reservoir to have full control of the flow traveling through the model. The overall experiment will contain more components to be attached to the rig such as PIV, camera, and data collectors. At this stage of the assembly, it should be enough to test the rig and make sure it is working.

Chapter 7

Conclusion

The aim of this thesis is to design an experiment rig that can test different models and be able to simulate the wall motion of the models. Linear actuators system has been successfully designed and programmed to apply a dynamic motion over the model's wall. This thesis is aimed to be able to simulate human upper airway model.

The efficiency of the actuators system is limited to human upper airway case and might need improvements to be able to test other types of models which require more force. Heavy duty linear actuators is an ideal choice to have enough force for every type of models but also the calculation of the force is just to make sure everything is working fine.

Another part needs improvements with respect to the model geometry is a scaffold that holds the model in the tank to make sure the model is stable during the experiment. Also, the actuator mount needs to be redesigned to fit the new actuators if the simulation needs new actuators with different sizes and dimensions.

Overall, the goal of this project has been achieved and the actuators are able to simulate the wall motion successfully. Through both experimental tests and research, a number of potenial issues were found that need improvements for future work such as Linear actuators resolution and accuracy. The actuators purchased is not the best in the market due to very low budget for undergraduate thesis students "$300 AUD". However, the best actuators that have been found on market to design an ideal system is around $4500 AUD for each unit.

7.1 Future Recommendations

It is recommended in this thesis that the work has been done successfully lead toward a future research and development of the experiment. As it may be easy to see from this project is that the topic is not an undergraduate level but it is a PhD topic that the department of engineering at Macquarie University is working on under the supervision of Dr. Shaokoon Cheng. The linear actuator system needs improvements to fit the highest load of force which may affect the performance of the current actuators and may need to be replaced for heavy-duty actuators to cover future studies.

Also, the Particle Image Velocimetry (PIV) Measurement Systems is a recommendation for such a studies that many relative research studies are working on using the similar setup of experiments. Particle Image Velocimetry (PIV) Measurement Systems should be able to produce high power light beam that can detect the fluid particles to study the flow characteristics. In similar studies, a High-speed camera has been used to take images of the flow at different stages.

This thesis is aimed to design the tank and the actuators system to be ready for developing the future studies. Also, the model has been made for this experiment is just to show that the actuators are able to apply dynamics force to simulate the wall motion. For future studies, casting new models is needed while this thesis is focusing on the experimental studies but focusing 80% on the design of the whole experiment and get it ready.

Chapter 8

Bibliography

1. Berme, N 2013, *Biomechanics of Normal and Pathological Human Articulating Joints* , 3rd edn, Springer Science & Business Media, New York.

2. Bilston, LE 2011, *Neural Tissue Biomechanics*, 10th edn, Springer Science & Business Media, Manchester.

3. Doblare, M 2015, *Biomechanics*, 4th edn, EOLSS Publications, Chicago.

4. Fung, YC 2014, *Biomechanics: Circulation*, 2nd edn, Springer Science & Business Media, Beijing.

5. Griffiths, IW 2016, *Principles of Biomechanics & Motion Analysis*, 5th edn, Lippincott Williams & Wilkins, London.

6. Kharmanda, G 2017, *Biomechanics: Optimization, Uncertainties, and Reliability*, 5th edn, John Wiley & Sons, London.

7. Knudson, D 2013, *Fundamentals of Biomechanics*, 6th edn, Springer Science & Business Media, Chicago.

8. Middleton, J 2009, *Computer Methods in Biomechanics and Biomedical Engineering 2*, 5th edn, CRC Press, London.

9. Mow, VC 2015, *Basic Orthopaedic Biomechanics & Mechano-biology*, 5th edn, Lippincott Williams & Wilkins, Manchester.

10. Robertson, G 2013, *Research Methods in Biomechanics*, 2E, 2nd edn, Human Kinetics, New York.

11. Si, X., Xi, J., & Kim, J. (2013). Effect of Laryngopharyngeal Anatomy on Expiratory Airflow and Submicrometer Particle Deposition in Human Extrathoracic Airways. *Open Journal of Fluid Dynamics*, 3(4), 286-301.

12. Genta, G. (2012). *Introduction to the Mechanics of Space Robots.* Dordrecht: Springer Science+Business Media B.V.

13. Phuong, N., & Ito, K. (2015). Investigation of flow pattern in upper human airway including oral and nasal inhalation by PIV and CFD. Building and Environment, 94, 504.

14. Taghirad, H. D. (2013). *Parallel robots: mechanics and control. CRC press.*

15. Mahtani, A., Sanchez, L., Fernandez, E., & Martinez, A. (2016). *Effective robotics programming with ROS: Find out everything you need to know to build powerful robots with the most up-to-date ROS*

16. Georgitzikis, V., Akribopoulos, O., & Chatzigiannakis, I. (2012). Controlling physical objects via the internet using the Arduino platform over 802.15. 4 networks. *IEEE Latin America Transactions, 10(3), 1686-1689.*

17. Banzi, M., & Shiloh, M. (2014). *Getting started with Arduino: the open-source electronics prototyping platform.* Maker Media, Inc.

18. Schubert, T. W., DAusilio, A., & Canto, R. (2013). Using Arduino microcontroller boards to measure response latencies. *Behavior research methods*, 45(4), 1332-1346.

19. Barbon, G., Margolis, M., Palumbo, F., Raimondi, F., & Weldin, N. (2016). Taking Arduino to the Internet of Things: the ASIP programming model. *Computer Communications*, 89, 128-140.

20. Kuan, W. H., Tseng, C. H., Chen, S., & Wong, C. C. (2016). Development of a computer-assisted instrumentation curriculum for physics students: Using LabVIEW and Arduino platform. *Journal of Science Education and Technology*, 25(3), 427-438.

21. Bruneo, D., Distefano, S., Longo, F., Merlino, G., Puliafito, A., & Zaia, A. (2017, June). Head in a Cloud: An approach for Arduino YUN virtualization. In *Global Internet of Things Summit (GIoTS)*, 2017 (pp. 1-6). IEEE.

22. Uma, K., Swetha, M., Manisha, M., Revathi, S. V., & Kannan, A. (2017). IOT based Environment Condition Monitoring System. *Indian Journal of Science and Technology, 10*(17).

23. Seder, R. R., & Dedi Ari Prasetya, S. T. (2017). 4 *Bases Smart Bed Prototype With Multiple Load Sensing To Control The Slope Of Multiple Bases Using Servo Motor* (Doctoral dissertation, Universitas Muhammadiyah Surakarta).

24. Kirshenbaum, N., & Robertson, S. (2016, June). Set&Motion: Tool for Authoring Interactive Stories with Sensors and Actuators. In *Proceedings of the The 15th International Conference on Interaction Design and Children* (pp. 554-559). ACM.

25. Graven, O. H., & Bjrk, J. (2016, December). The use of an Arduino pocket lab to increase motivation in Electrical engineering students for programming. In *Teaching, Assessment, and Learning for Engineering (TALE), 2016 IEEE International Conference on* (pp. 239-243). IEEE.

Chapter 9

Abbreviations

HUA	Human Upper Airway
CAD	Computer Aided Design
CFD	Compotetional Fluid Dynamics
AAA	abdominal aortic aneurysm
PIV	Particle Image Velocimetry
SLA	stereolithography
PVA	polyvinyl alcohol
FSI	Fluid-structure interaction
AAA	abdominal aortic aneurysm

Appendix A

Appendix

Code part 1 :

```
#include <Servo.h>
#include <TimerOne.h>            //Timer number one library
double t = 0;
float y = 0;
float f = 0.2; // frequency, and changing it will change speed of actuation
const double pi = 3.141593;
double w = 2 * pi * f;
float c = 0;   // phase shift
float d = 0;   // offset
float a = 10;  // max position amplitude
float resolution = 80;   // sine function number of samples per cycle, do not exceed 1000
Servo myservo, myservo1, myservo2;  // create servo object to control a servo
boolean flag = false;
float sample_step;

float val = 0;   // variable to read the value from the analog pin
int i = 0;
void setup()
{
  myservo.attach(9);  // attaches the servo on pin 9 to the servo object
  myservo1.attach(10);  // attaches the servo on pin 10 to the servo object
  myservo2.attach(11);  // attaches the servo on pin 11 to the servo object
  Serial.begin(115200);
  sample_step = (1 / f) * 1000 / resolution;
  myservo.writeMicroseconds(1000);
  myservo1.writeMicroseconds(1000);
  myservo2.writeMicroseconds(1000);
  delay(3000);
  myservo.writeMicroseconds(1500);
  myservo1.writeMicroseconds(1500);
  myservo2.writeMicroseconds(1500);
  delay(3000);
}
```

Code Part 2 :

```
void loop()
{

  y = a * sin(w * t + c) + d;
  y=y*100;
  int k = map(y, -1500, 1500, 1000, 2000);//(y + 10) * 100;
  myservo.writeMicroseconds(k);
  myservo1.writeMicroseconds(k);
  myservo2.writeMicroseconds(k);
  Serial.print(k);
  Serial.print("  ");
  Serial.println(t);
  while (i < sample_step)
  {
    delay(1);
    i++;
  }
  i = 0;
  t = t + (1 / f) / resolution;
}
```

100mm L12 Actuator
Actual Size

Benefits

→ Compact
→ Simple control
→ Low voltage
→ Equal push/pull
→ Easy mounting

Applications

→ Robotics
→ Appliances
→ Toys
→ RC vehicles
→ Automotive
→ Industrial Automation

Miniature Linear Motion Series · L12

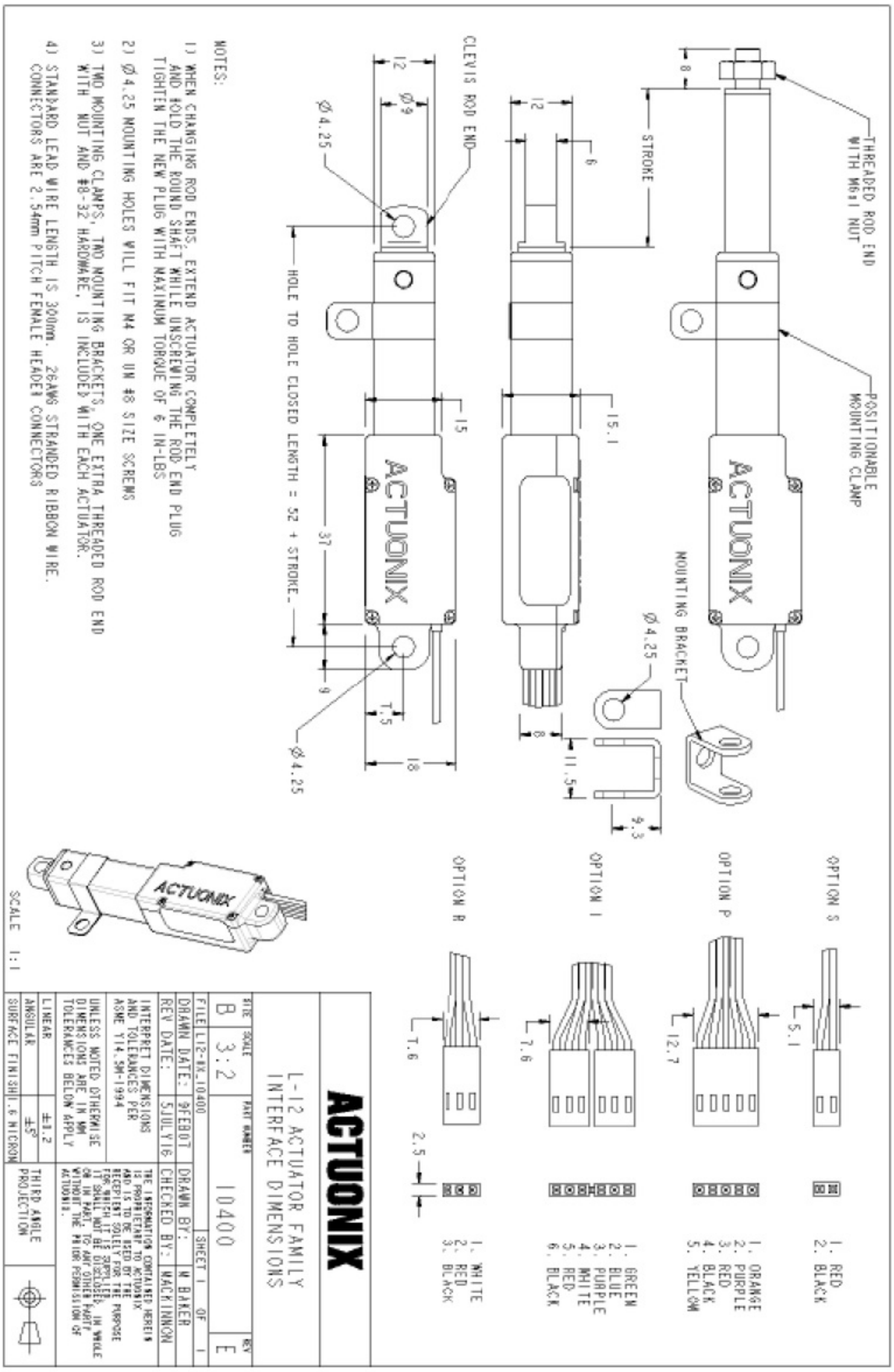
Actuonix Motion Devices unique line of Miniature Linear Actuators enables a new generation of motion-enabled product designs, with capabilities that have never before been combined in a device of this size. These small linear actuators are a superior alternative to designing with awkward gears, motors, servos, and linkages.

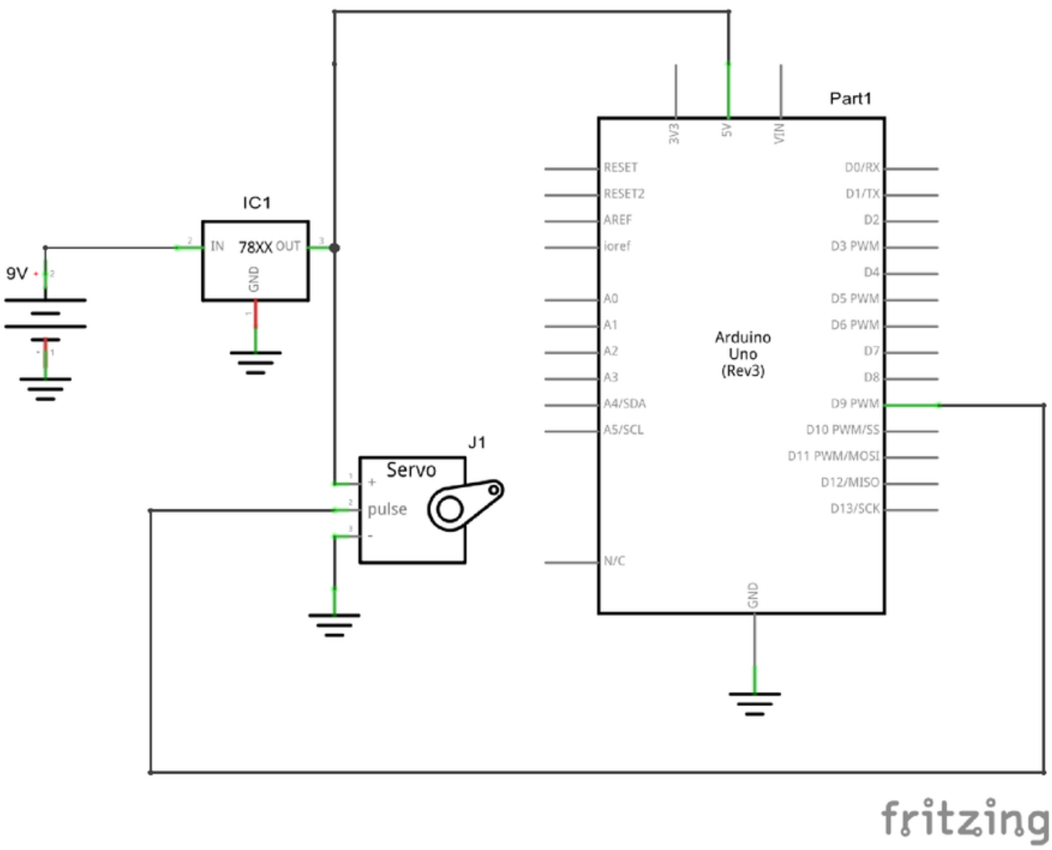
Actuonix's L series of micro linear actuators combine the best features of our existing micro actuator families into a highly flexible, configurable, and compact platform with an optional sophisticated on-board microcontroller. The first member of the L series, the L12, is an axial design with a powerful drive-train and a rectangular cross section for increased rigidity. But by far the most attractive feature of this actuator is the broad spectrum of available configurations.

L12 Specifications

Gearing Option	50:1		100:1	210:1
Peak Power Point	17N @ 14mm/s		31N @ 7mm/s	62N @ 3.2mm/s
Peak Efficiency Point	10N @ 19mm/s		17N @ 10mm/s	36N @ 4.5mm/s
Max Speed *(no load)*	25mm/s		13mm/s	6.5mm/s
Max Force *(lifted)*	22N		42N	80N
Back Drive Force *(static)*	12N		22N	45N
Stroke Option	**10 mm**	**30mm**	**50mm**	**100mm**
Mass	28 g	34 g	40 g	56 g
Repeatability *(-I,-R,-P&LAC)*	±0.1 mm	±0.2 mm	±0.3 mm	±0.5 mm
Max Side Load *(extended)*	50N	40N	30N	15N
Closed Length *(hole to hole)*	62mm	82mm	102mm	152mm
Potentiometer *(-I, -R, -P)*	1kΩ±50%	3kΩ±50%	6kΩ±50%	11kΩ±50%
Voltage Option		**6VDC**		**12VDC**
Max Input Voltage		7.5V		13.5V
Stall Current		460mA		185mA
Standby Current *(-I/-R)*		7.2mA		3.3mA
Operating Temperature		-10°C to +50°C		
Potentiometer Linearity		Less than 2.00%		
Max Duty Cycle		20 %		
Audible Noise		55dB @ 45cm		
Ingress Protection		IP-54		
Mechanical Backlash		0.2mm		
Limit Switches *(-S)*		Max. Current Leakage: 8uA		
Maximum Static Force		200N		

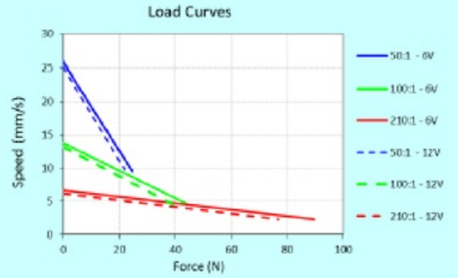
1 - Control Option Specific values are identified with -I, -R, -P, -S, and LAC
2 - 1 N (Newton) = 0.225 lbf (pound-force) & 25.4mm=1 Inch
3 - A powered-off actuator will statically hold a force up to the Backdrive Force
4 - Actuators should be tested in each specific application to determine their effective life under those loading conditions and environment.

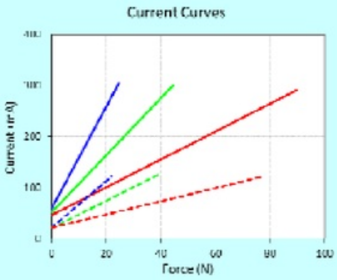

THREADED ROD END WITH M6x1 NUT
POSITIONABLE MOUNTING CLAMP
ACTUONIX
MOUNTING BRACKET
STROKE
CLEVIS ROD END
HOLE TO HOLE CLOSED LENGTH = 52 + STROKE
OPTION S
1. RED
2. BLACK
OPTION P
1. ORANGE
2. PURPLE
3. RED
4. BLACK
5. YELLOW
OPTION I
1. GREEN
2. BLUE
3. PURPLE
4. WHITE
5. RED
6. BLACK
OPTION R
1. WHITE
2. RED
3. BLACK
NOTES:
1) WHEN CHANGING ROD ENDS, EXTEND ACTUATOR COMPLETELY AND HOLD THE ROUND SHAFT WHILE UNSCREWING THE ROD END PLUG TIGHTEN THE NEW PLUG WITH MAXIMUM TORQUE OF 6 IN-LBS
2) Ø4.25 MOUNTING HOLES WILL FIT M4 OR UN #8 SIZE SCREWS
3) TWO MOUNTING CLAMPS, TWO MOUNTING BRACKETS, ONE EXTRA THREADED ROD END WITH NUT AND #8-32 HARDWARE, IS INCLUDED WITH EACH ACTUATOR.
4) STANDARD LEAD WIRE LENGTH IS 300mm. 26AWG STRANDED RIBBON WIRE. CONNECTORS ARE 2.54mm PITCH FEMALE HEADER CONNECTORS
SCALE 1:1
L-12 ACTUATOR FAMILY INTERFACE DIMENSIONS
SIZE B
SCALE 3:2
PART NUMBER 10400
REV E
FILE L12-XX_10400
SHEET 1 OF 1
DRAWN DATE: 9FEB07
DRAWN BY: M BAKER
REV DATE: 5JULY16
CHECKED BY: MACKINNON
INTERPRET DIMENSIONS AND TOLERANCES PER ASME Y14.5M-1994
UNLESS NOTED OTHERWISE DIMENSIONS ARE IN MM TOLERANCES BELOW APPLY
LINEAR ±0.2
ANGULAR ±5°
SURFACE FINISH 1.6 MICRON
THIRD ANGLE PROJECTION



IC1
78XX
IN
OUT
GND
9V
Part1
3V3
5V
VIN
RESET
RESET2
AREF
ioref
A0
A1
A2
A3
A4/SDA
A5/SCL
N/C
D0/RX
D1/TX
D2
D3 PWM
D4
D5 PWM
D6 PWM
D7
D8
D9 PWM
D10 PWM/SS
D11 PWM/MOSI
D12/MISO
D13/SCK
Arduino
Uno
(Rev3)
GND
J1
Servo
+
pulse
-
fritzing

L12 Specifications





Model Selection

L12 options are identified according to the following scheme:

L12-SS-GG-VV-C

feature	*Options*
SS: Stroke Length	**10, 30, 50, 100**
GG: Gear reduction ratio (refer to load curves above)	**50, 100, 210** (lower ratios are faster but push less force, and vice versa)
VV: Voltage	**6, 12** (DC volts)
C: Controller	**S** Limit Switches **P** Potentiometer Feedback **I** Integrated Controller **R** RC Servo Integrated Controller

L12 Controller Options

Option S – End of Stroke Limit Switches

WIRING: (see last page for pin numbering)
1 - Red – Motor V+
2 – Black – Motor V- (Gnd)

The –S actuators have limit switches that will turn off power to the motor when the actuator reaches within 0.5mm of the end of stroke. Internal diodes allow the actuator to reverse away from the limit switch. The limit switches cannot be moved once the actuator is manufactured. While voltage is applied to the motor power pins, (1 & 2) the actuator extends. Reverse the polarity and the actuator retracts. This can be accomplished manually with a DPDT switch or relay, or using an H-Bridge circuit. The –S model cannot be used with the LAC control board.

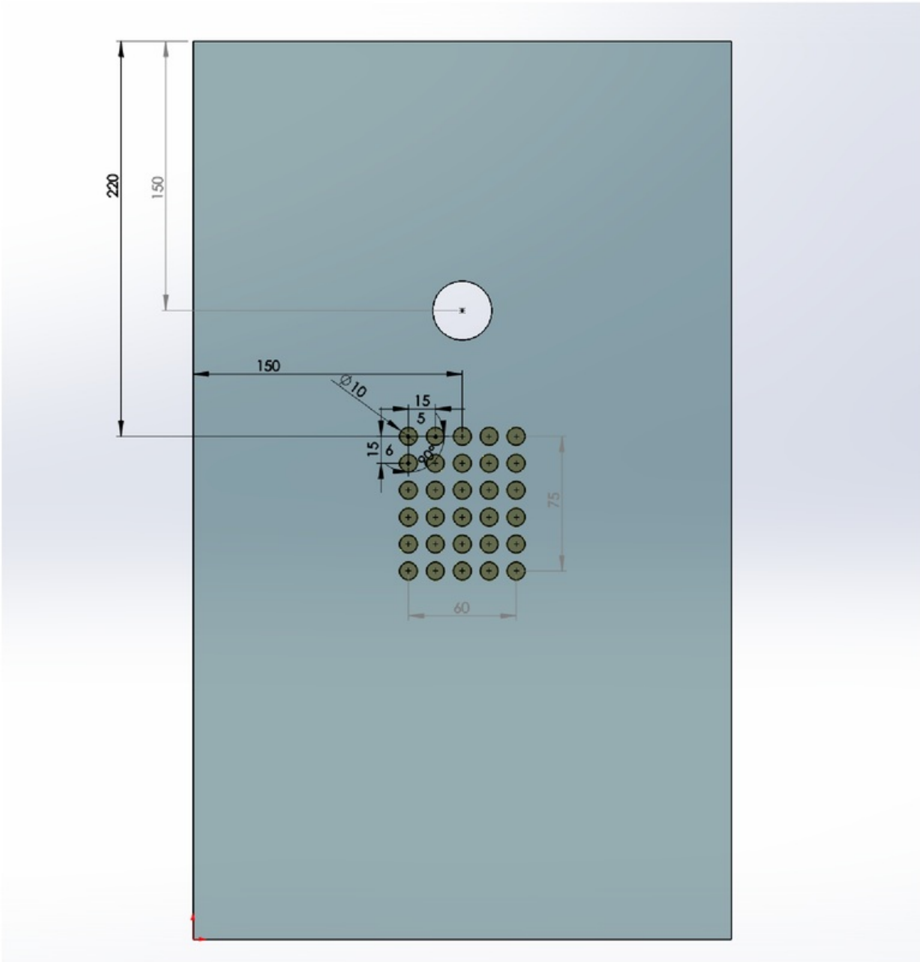
Option P – Potentiometer Position Feedback

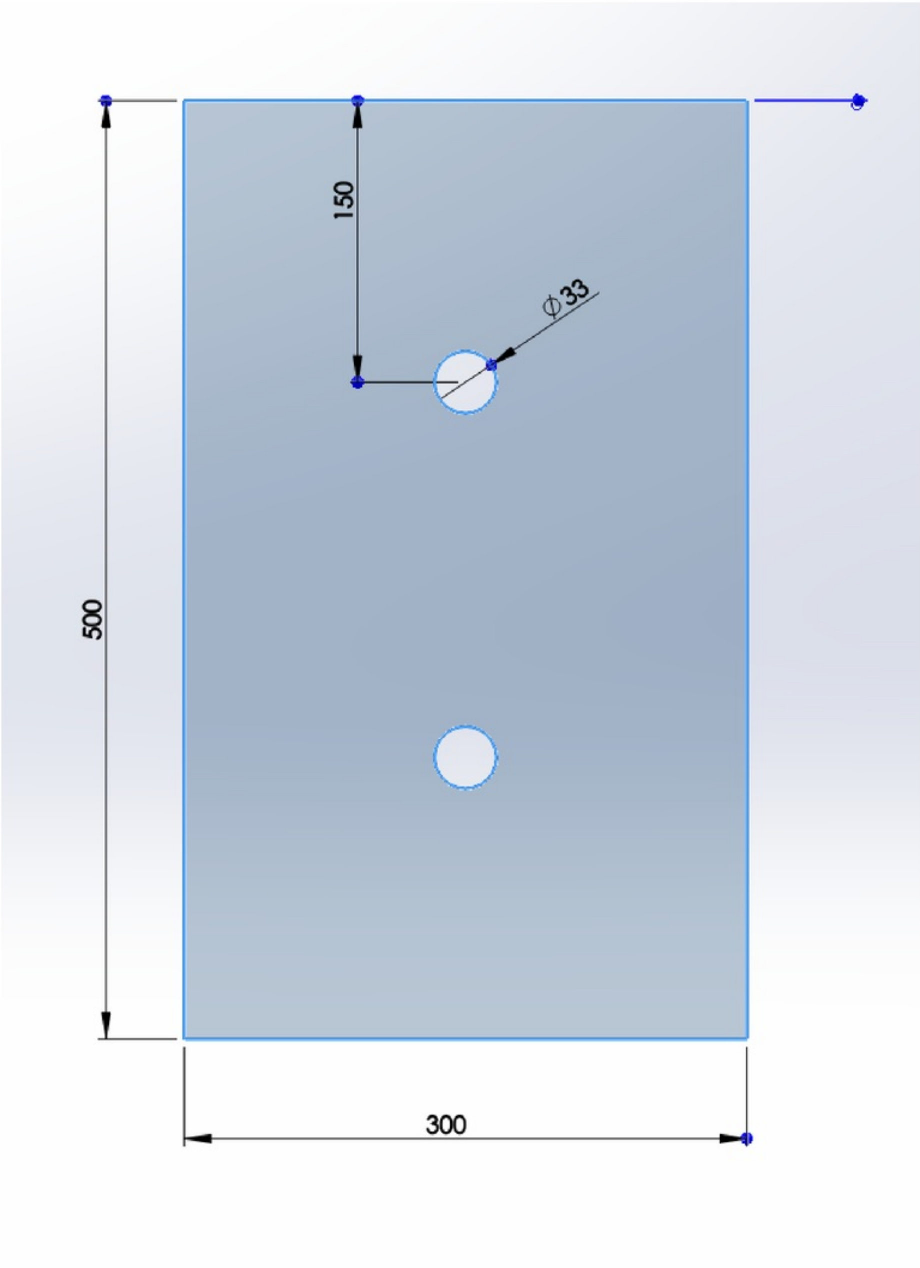
WIRING: (see last page for pin numbering)
1 - Orange – Feedback Potentiometer negative reference rail
2 - Purple – Feedback Potentiometer wiper
3 - Red – Motor V+ (6V or 12V)
4 - Black – Motor V- (Ground)
5 - Yellow – Feedback Potentiometer positive reference rail

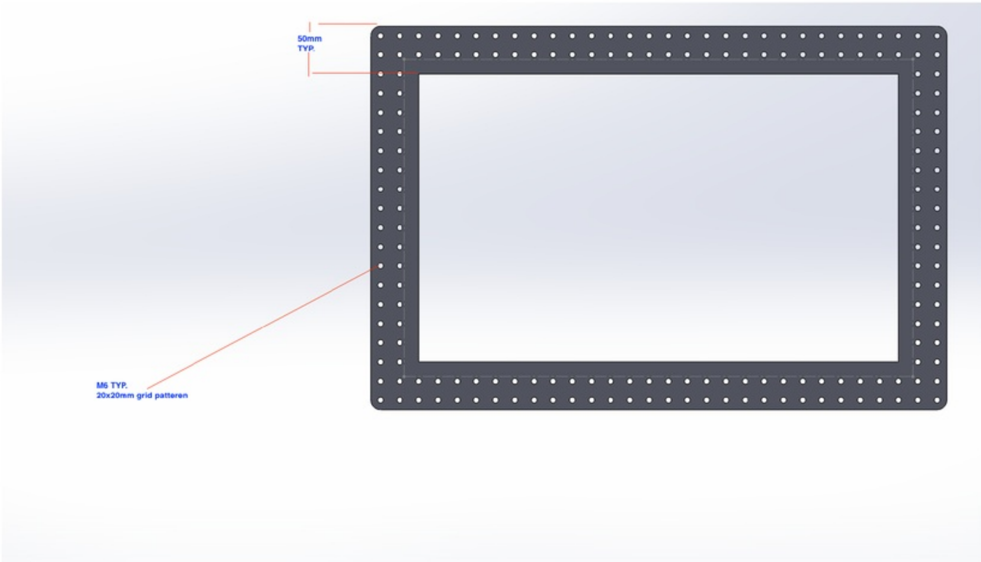
The –P actuators have no built in controller, but do provide an analog position feedback signal that can be input to an external controller. While voltage is applied to the motor power pins, (3 & 4) the actuator extends. Reverse the polarity and the actuator retracts. This can be accomplished manually with a DPDT switch or relay, or using an H-Bridge circuit. Position of the actuator stroke can be monitored by providing any stable low and high reference voltage on pins 1 & 5, then reading the position signal on pin 2. The voltage on pin 2 will vary linearly between the two reference voltages in proportion to the position of the actuator stroke.

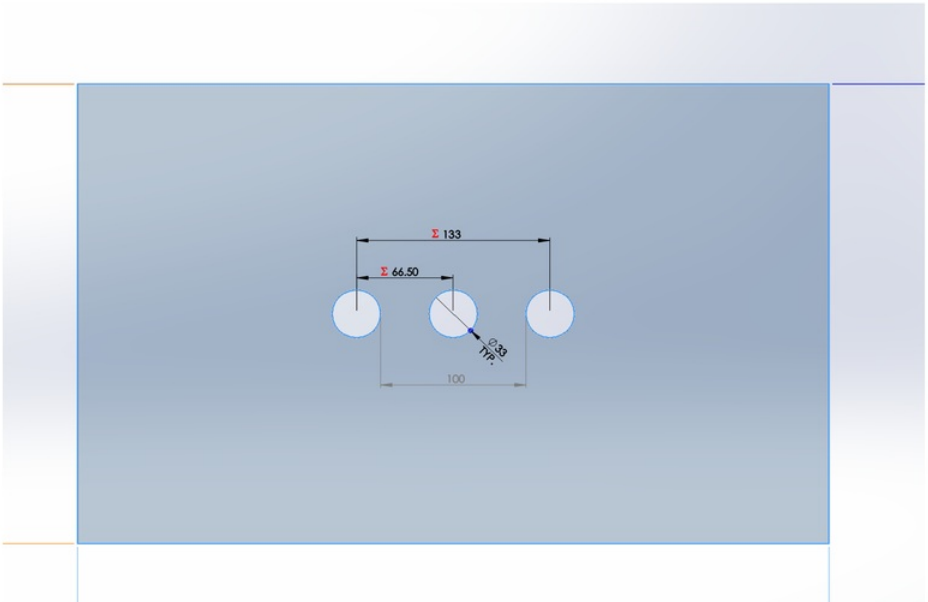
The L12 –P actuator can be used as a linear servo by connecting the actuator to an external controller such as the LAC board offered by Firgelli. This control board reads the position signal from the L12, compares it with your input control signal then commands the actuator to move via an on-board H-bridge circuit. The LAC allows any one of the following control inputs: Analog 0-5V or 4-20mA, or Digital 0-5V PWM, 1-2ms Standard RC, or USB. The RC input effectively transforms your L12 into a linear servo, which is a direct replacement for any common hobby servo used in RC toys and robotics. Refer to the LAC datasheet for more details.

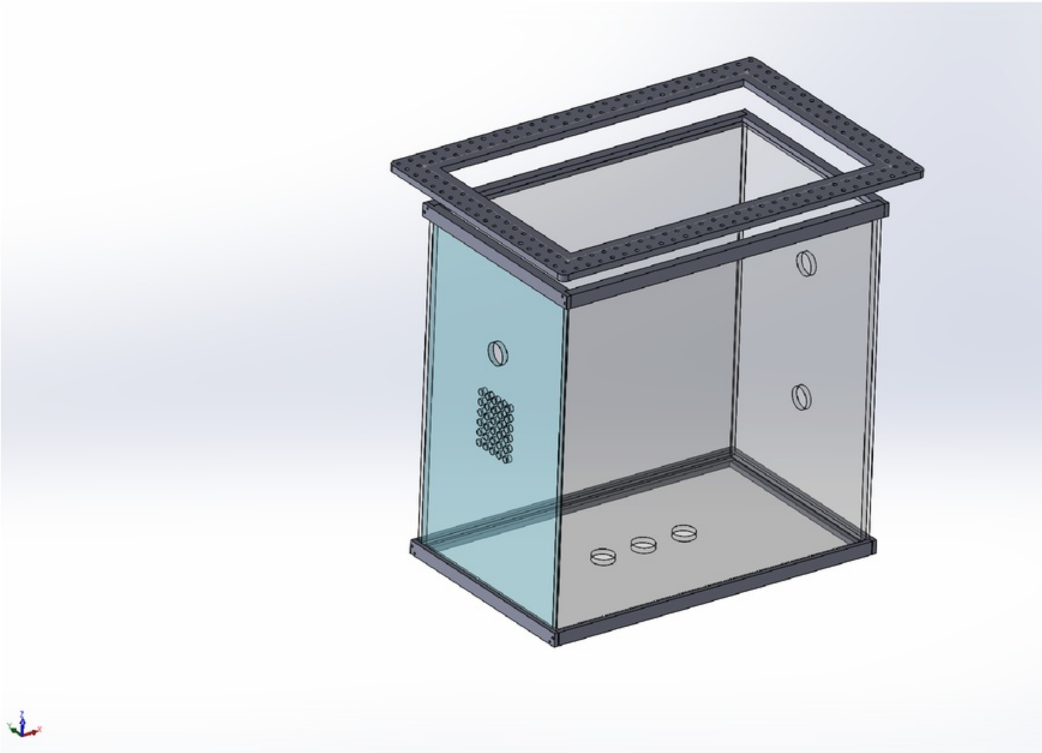
Actuonix Motion Devices Inc
580 Starling Lane
Victoria, BC, V9E 2A9
Canada
1 (206) 347-9684 *phone*
1 (888) 225-9198 *toll-free*
1 (206) 347-9684 *fax*
sales@actuonix.com
www.actuonix.com


220
150
150
⌀10
15
5
15
6
90°
75
60


150
ϕ33
500
300


50mm
TYP.
M6 TYP.
20x20mm grid patteren


Σ 133
Σ 66.50
Ø33
TYP.
100



WACKER

ELASTOSIL®

ELASTOSIL® RT 601 A/B

RTV-2 SILICONE RUBBER

Product description

ELASTOSIL® RT 601 A/B is a pourable, addition-curing RTV-2 silicone rubber.

Special features

- two-part, 9 : 1 mixing ratio
- low viscosity
- medium cured hardness
- excellent tensile strength
- crystal clear vulcanizate

Application

- all-round potting compound
- manufacture of molded articles by casting

Processing

Caution:
Only components A and B with the same lot number may be processed together!

Surface preparation:
All surfaces must be clean and free of contaminants that will inhibit the cure of ELASTOSIL® RT 601 A/B. Examples of inhibiting contaminants are sulfur containing materials, plasticizers, urethanes, amine containing materials and organometallic compounds - especially organotin compounds. If a substrate's ability to inhibit cure is unknown, a small scale test should be run to determine compatibility.

Mixing:
Component A of ELASTOSIL® RT 601 contains the platinum catalyst, component B the crosslinker. Even traces of the platinum catalyst may cause gelling of the component containing the crosslinker. Therefore tools (spatula, stirrers, etc.) used for handling the platinumcontaining component or the catalyzed compound must not come into contact with this component.

The two components should be thoroughly mixed at a 9 : 1 ratio by weight or volume.

To eliminate any air introduced during dispensing or trapped under components or devices a vacuum encapsulation is recommended.

Curing:
Curing time of addition curing silicone rubber is highly dependent on temperature, size and heat sink properties of the component being potted.

The reactivity can be adjusted within wide limits by adding Catalyst EP or Inhibitor PT 88 to suit the processing requirements of the particular application. Catalyst EP increases the reactivity, i. e., pot life and curing time are reduced. Inhibitor PT 88 is a pot life extender and prolongs pot life and curing time. Further information is given in our leaflet "Catalyst EP/Inhibitor PT88".

We recommend running preliminary tests to optimize conditions for the particular application.

Comprehensive instructions are given in our leaflet "ELASTOSIL® - PROCESSING RTV-2 SILICONE RUBBERS".

Temperature	Curing time, thickness 1 cm
23 °C	24 h
70 °C	20 min
100 °C	10 min

Storage

The 'Best use before end' date of each batch is shown on the product label.

Storage beyond the date specified on the label does not necessarily mean that the product is no longer usable. In this case however, the properties required for the intended use must be checked for quality assurance reasons.

WACKER ELASTOSIL®

require special handling precautions.

Safety notes

According to the latest findings, the addition-curing silicone rubber ELASTOSIL® RT 601 A/B contains neither toxic or corrosive substances which would require special handling precautions.

Comprehensive instructions are given in the corresponding Material Safety Data Sheets. They are available on request from WACKER subsidiaries or may be printed via WACKER web site http://www.wacker.com.

Product data

Typical general characteristics	Inspection Method	Value
Product data (uncured)		
Component A		
Color		colorless
Viscosity at 23 °C	ISO 3219	5000 mPa s
Density at 23 °C		1,03 g/cm³
Component B		
Color		colorless
Viscosity at 23 °C	ISO 3219	40 mPa s
Density at 23 °C		0,97 g/cm³
Product data (catalyzed A+B)		
Mix ratio (pbw)	A : B	9 : 1
Viscosity of mix at 23 °C	ISO 3219	3500 mPa s
Pot life at 23 °C, up to 20000 mPa s		90 min
Platinum-catalyst in component		A
Product data (cured)		
Color		colorless, transparent
Density at 23 °C	ISO 2781	1,02 g/cm³
Hardness Shore A	ISO 868	45
Tensile strength	DIN ISO 37	6,00 N/mm^2
Elongation at break	ISO 37	100 %
Volume resistivity	IEC 60093	10^{15} Ω cm
Permittivity	IEC 60250	2,8

Cured for 30 min at 150 °C in a circulating air oven.
These figures are only intended as a guide and should not be used in preparing specifications.

For technical, quality, or product safety questions, please contact:

Wacker Chemie AG
Hanns-Seidel-Platz 4
81737 München, Germany
info.silicones@wacker.com

www.wacker.com