Report

Abstract

Inspired by the simple swivel wheel, this paper presents a novel prototype concept for a modular wheel module that can be easily adapted in any number for robot bases and other applications. Using Active Split Offset Castors (ASOC), the module can achieve true, instantaneous, omnidirectional movement via 3 independent degrees of freedom. The simple design has high power-efficiency, noise-free operation and can carry high load capacities when compared to existing solutions for holonomic movement. This novel prototype concept, named the MBot-One, possesses unique advantages and capabilities, making it a promising, versatile solution for omnidirectional movement.

Introduction

Omnidirectional motion is an important capability of mobile robots. Such robots in ground vehicles allow independent motion along 2 translational directions and planar rotation, i.e. they have 3 independent degrees of freedom (DOF). Although there are current solutions that enable holonomic capabilities, there is no simple, modular design that can be adapted in different configurations for different applications (Figure 1). Hence, this project aims to design an omnidirectional robot wheel module that is modular and maneuverable in tight spaces with complete 3 independent DOF.

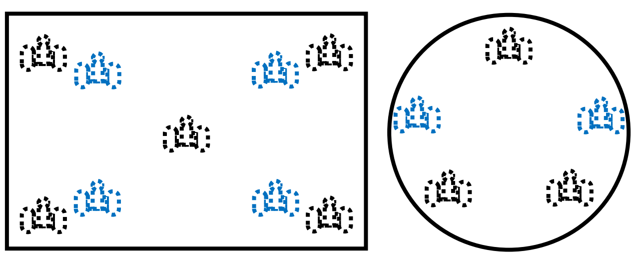


Figure 1: Different possible configurations to move a robot base

This paper discusses the design and concept of the MBot-One, electronics interfacing, and its unique features and novel modularity.

Related Work

Currently, there are 2 main ways to achieve omnidirectional motion. First, the use of special wheels such as Omni wheels[1] and Mecanum wheels[2] (Figure 2, 3). Most of these designs achieve traction in one direction and allow passive motion in another. However, these wheels have limited load capacity as they use thin rollers to support payloads. Moreover, the small diameter of the rollers limits the height of traversable obstacles. The rollers can also generate unnecessary vibrations when in motion, especially on uneven ground, because of non-continuous contact with ground. Hence, these wheels can be impractical to be used on surfaces with dirt and debris.

Figure 2: Omni Wheel

Figure 3: Mecanum Wheel

Another method is powered castor wheels[3]. The basic structure of a powered castor wheel comprises of a regular wheel and an offset steering. Two motors are needed, one for steering **ϕ** and one for driving **ρ** (Figure 4)[4]. However, this method involves indirect transmission via complex gearing in order to mount the 2 necessary motors.

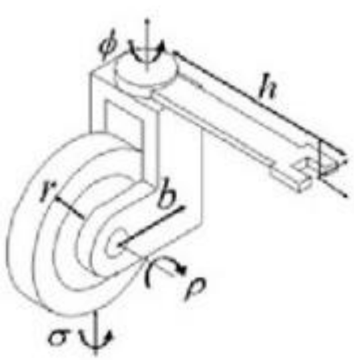


Figure 4: The structure of a powered castor wheel

The design presented in this paper falls within this category. However, two key differences were integrated into the design: direct drive hub motors and a split offset castor.

As proposed by researchers from the Massachusetts Institute of Technology (MIT)[5], the Active Split Offset Castor (ASOC) system consists of two independently driven coaxial wheels, separated by a distance and connected to the rotating joint by an offset (Appendix A). Controlling the velocities of the active wheels allows the velocity of the of the joint to be changed, achieving holonomic motion of the joint.

In summary, current power castor designs are not very modular, limiting their versatility for various applications. Also, as mentioned earlier, complex motor components are used.

Concept and Kinematics of the MBot-One

The main inspiration for the MBot-One is the common swivel castor, consisting of a passive roller(s) and an offset rotating joint (Figure 5). Producing a moment about the rotating joint allows the roller to roll in all directions to achieve smooth, omnidirectional motion.

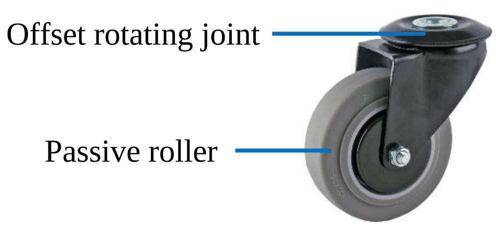


Figure 5: A swivel castor

Similarly, power castor wheels minimise scrubbing friction and instead rely on rolling friction to steer. Thus, since less energy is loss as friction and sound when the wheels are turned[6], this design is highly power efficient. They can also support higher loads due to a more rigid build as compared to special wheels.

Therefore, the main goals of the MBot-One design were to enhance the modularity and efficiency of power castors.

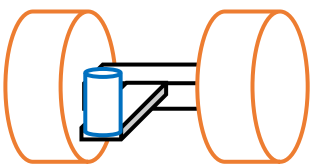


Figure 6: Rough outline of the MBot-One design

A simplified diagram of the MBot-One is shown in Figure 6. Using inverse kinematics, a relationship between the velocities of both wheels (orange) and the offset rotating joint (blue) can be established in a localised coordinate system XOY (Figure 7).

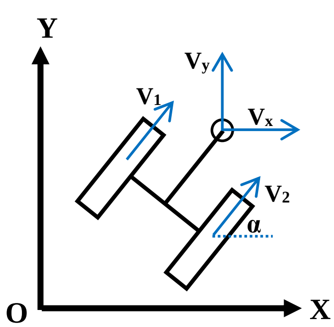


Figure 7: Velocities in a localised coordinate system

By controlling the inertial velocities of both wheels, arbitrary and unique velocities of the offset rotating joint can be achieved:

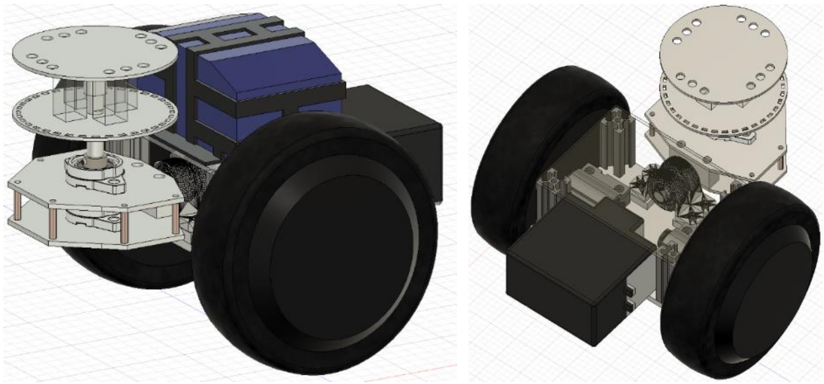
$$\boldsymbol{V_x} = \left(\frac{1}{2}cos\boldsymbol{\alpha} - \frac{S}{D}sin\boldsymbol{\alpha}\right)(\boldsymbol{V_1}) + \left(\frac{1}{2}cos\boldsymbol{\alpha} + \frac{S}{D}sin\boldsymbol{\alpha}\right)(\boldsymbol{V_2})$$

$$\boldsymbol{V_y} = \left(\frac{1}{2}sin\boldsymbol{\alpha} + \frac{S}{D}cos\boldsymbol{\alpha}\right)(\boldsymbol{V_1}) + \left(\frac{1}{2}sin\boldsymbol{\alpha} - \frac{S}{D}cos\boldsymbol{\alpha}\right)(\boldsymbol{V_2})$$

Full derivation of the kinematics can be found in Appendix B.

Design and Components

The overall build for the MBot-One is shown in Figure 8 below. Due to its simple structure, the assembly did not involve welding and only required metric screws and nuts. This section will discuss the chassis (main body), electronics, and damping with dielectric elastomers.



A fully labelled model and general specifications for the MBot-One can be found in Appendix C.

Figure 8: The MBot-One

1. Main Chassis

The main chassis is split into the central section and the support section (Figure 9). It comprises of the robot frame and motors.

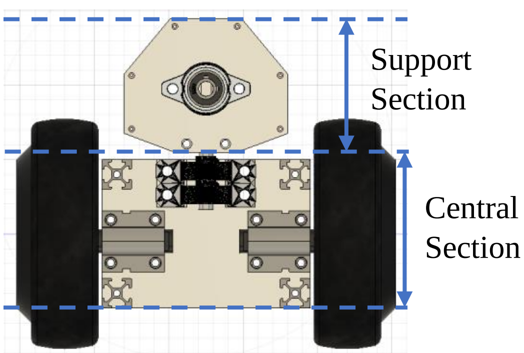


Figure 9: Two sections of the MBot-One

a. Central Section

Two brushless DC (BLDC) motors are mounted coaxially to the main plate. BLDC motors provide the advantage of direct drive to the wheels (Appendix D). Hence, unlike traditional DC motors, no complex gearing was required. Two P000 pillow blocks (K000 bearings) create a revolute joint for the central section to rotate independently from the support section. This passive suspension allows MBot-One to maintain traction on uneven ground, providing stability and reliable motion (Appendix E).

b. Support Section

Two FL000 pillow blocks (K000 bearings) create a revolute joint that allow the DE damping system and mounting plate to rotate independently from the base of the support section.

2. Electronics

MBot-One is controlled by an ESP32 microcontroller. The ESP32 provided sufficient general-purpose input/output (GPIO) pins to control the BLDC motor drivers and FC-03 LM393 infra-red encoders. It also provided Bluetooth and Wi-Fi capabilities.

The BLDC motor drivers have individual control pins to enable (on/off), change the direction and speed of the motors (Appendix F). An input signal pin receives the number of steps moved by the motor. A pulse width modulation (PWM) signal is used to control the speed of the motor. The enable and direction pins were turned on or off by applying 5V or 0V respectively.

A bi-directional logic level converter was used to boost the 3.3V output voltage of the ESP32 GPIO pins to 5V to operate the motor drivers. An EMCO AGH60P-5 DC to HV DC converter provided the high voltage needed to operate the DE damping system.

3. Dielectric elastomer (DE) Damping System

DEs are a suitable material for damping vibrations due to their viscoelasticity[7]. When a potential difference V is applied to the DE layer, the elastomer compresses and linear expansion occurs (Figure 10). This changes the ability of the material to compress when a weight pushes down on it. Thus, by varying the magnitude of V, the extent of contraction can be varied, changing the damping ability of the DE. This effect is magnified when many DE layers do work as one unit[8]. Hence, as a novel variable damping solution, DE stacks were adopted for the MBot-One to support payloads.

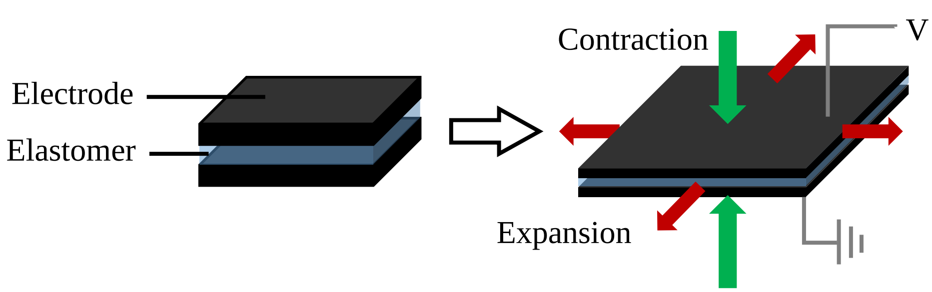


Figure 10: Illustration of the DE mechanism

Four 2.0cm tall DE stacks were fabricated to be used as a damping system for payloads mounted onto MBot-One. 3M 4905 VHB Tape elastomer (0.5mm thickness) was used to due to its affordability and desirable properties[9]. Carbon grease was used for the electrodes due to its ease of application for easy fabrication. Each layer was a 2.5cm square of elastomer with 2.0cm square electrode. Each stack was fabricated manually with an alternating configuration (Figure 11). Test sample results can be viewed in Appendix G.

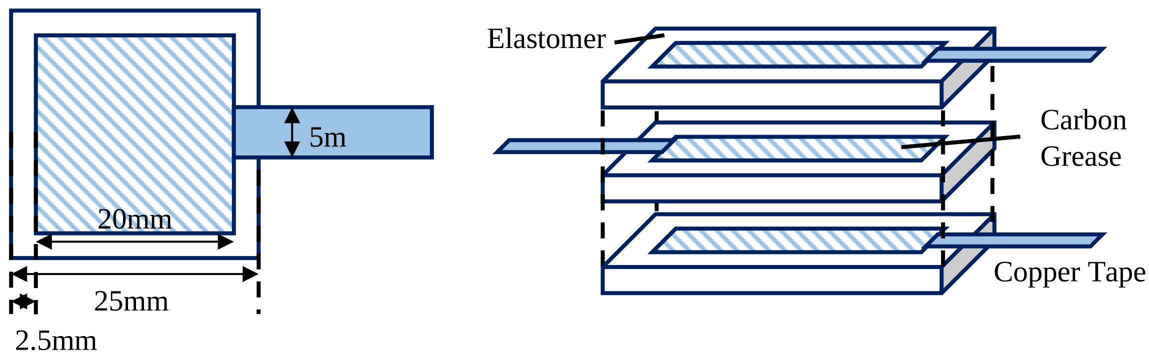


Figure 11: DE layer measurements and the DE stack layout

Conclusion and Future Work

The final MBot-One (Figure 8) is a compact ASOC system featuring a unique damping concept. Since the mounting plate and robot body are one unit, MBot-One is an independent module. The ability to operate locally with its own set of electronics and battery as an independent module gives MBot-One a novel modularity. Thus, this is simply the first step towards being integrated into a distributive control system.

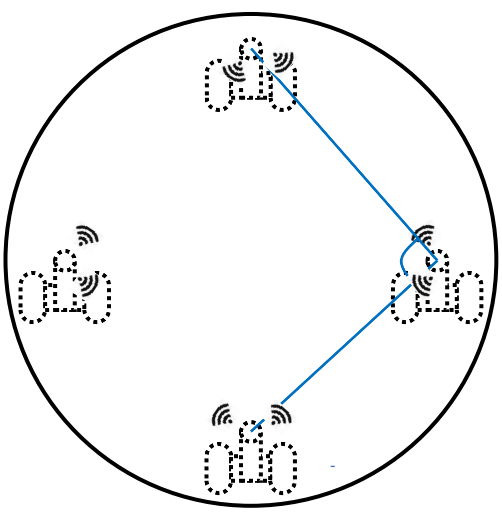


Figure 12: The arrangement of multiple MBot-One units for synchronised movement

Only a minimum of 2 MBot-One modules are required to achieve 4 independent DOF. Since the V_1, V_2 and trajectory of each MBot-One module relates to their distance and bearing from one another, it is possible to compute the desired V_1 and V_2 velocities of each module to allow the synchronised movement of all modules in a desired path. Thus, multiple MBot-One units can be arranged and synchronised together in any configuration to act as one omnidirectional system. Together with a self-calibration mechanism and wireless communication, the MBot-One modules would unlock a vast spectrum of applications by enabling the omnidirectional mobility of many systems.

References

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Appendices

Appendix A

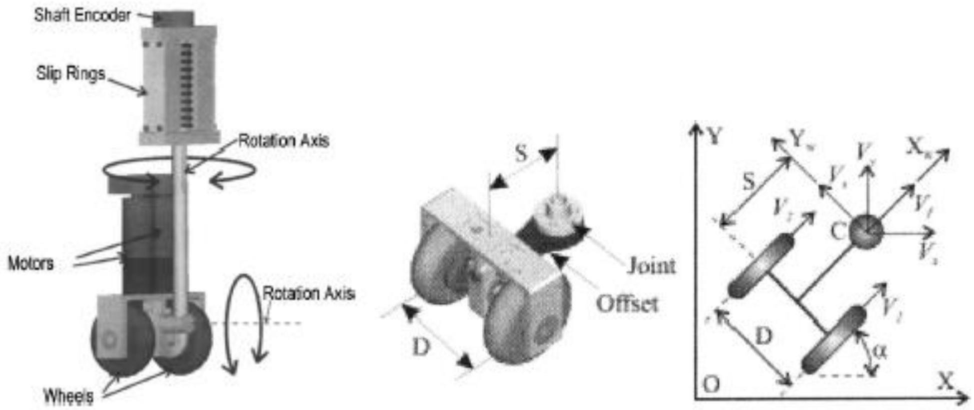


Figure A.1: MIT's ASOC module and its coordinate system

Appendix B

For a split offset castor with 2 coaxial wheels separated by distance D, and connected to an offset joint of distance S, a localised coordinate system XOY (Figure A.2) is defined.

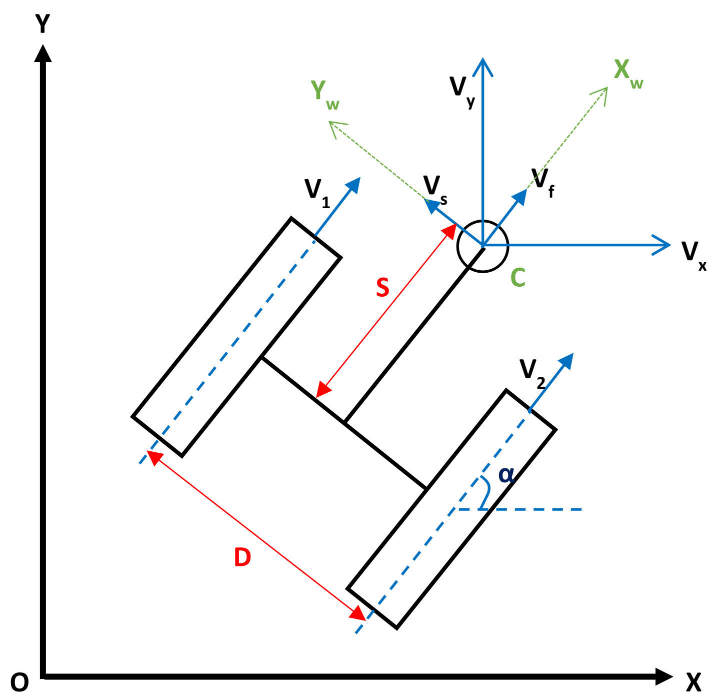


Figure A.2: Coordinate system and MBot-One kinematics

Wheel velocities are V_1 and V_2, and joint velocities with respect to ground are V_f and V_s. The two vectors **u** and $\mathbf{q_w}$ are defined as:

$$\boldsymbol{u} = [V1 \quad V2]^T$$

$$\dot{\boldsymbol{q}}_{\boldsymbol{w}} = [Vf \quad Vs]^T$$

From there, the Jacobian matrix of the ASOC module in the moving coordinate frame XwCYw is $\mathbf{J_w}$, where $\mathbf{q_w} = \mathbf{J_w}\,\mathbf{u}$:

$$\boldsymbol{J}_{\boldsymbol{w}} = \begin{bmatrix} 1/2 & 1/2 \\ S/D & S/D \end{bmatrix}$$

The velocity of the joint in the inertial frame **q** is given by:

$$\boldsymbol{q} = [Vx \quad Vy]^T = \boldsymbol{R}\dot{\boldsymbol{q}}_{\boldsymbol{w}} = \begin{bmatrix} \boldsymbol{cos\,\alpha} & \boldsymbol{-sin\alpha} \\ \boldsymbol{sin\alpha} & \boldsymbol{cos\alpha} \end{bmatrix} \dot{\boldsymbol{q}}_{\boldsymbol{w}}$$

where $\boldsymbol{\alpha}$ is the orientation of the ASOC module with respect to the X axis in XOY.

The kinematic relationship between the inertial velocity of the joint and the two wheel velocities is:

$$\dot{\boldsymbol{q}} = \boldsymbol{R}\dot{\boldsymbol{q}}_{\boldsymbol{w}}\boldsymbol{u} = \boldsymbol{J}\boldsymbol{u}$$

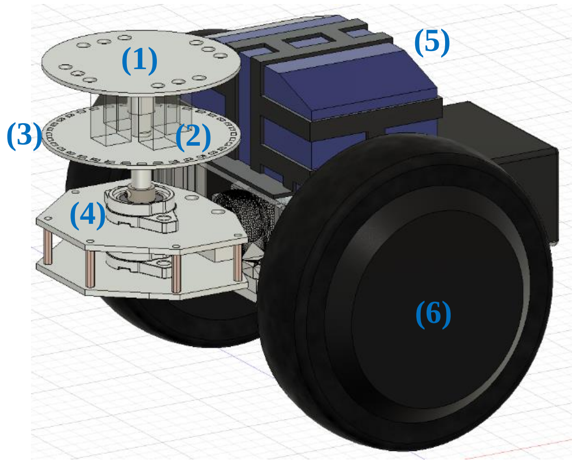
where **J** is the Jacobian matrix for the ASOC module in XOY:

$$J = \begin{bmatrix} \boldsymbol{1/2cos\alpha - S/Dsin\alpha} & \boldsymbol{1/2cos\alpha + S/Dsin\alpha} \\ \boldsymbol{1/2sin\alpha + S/Dcos\alpha} & \boldsymbol{1/2sin\alpha - S/Dcos\alpha} \end{bmatrix}$$

The determinant of **J** is therefore:

$$det\,J = -S/D$$

Appendix C



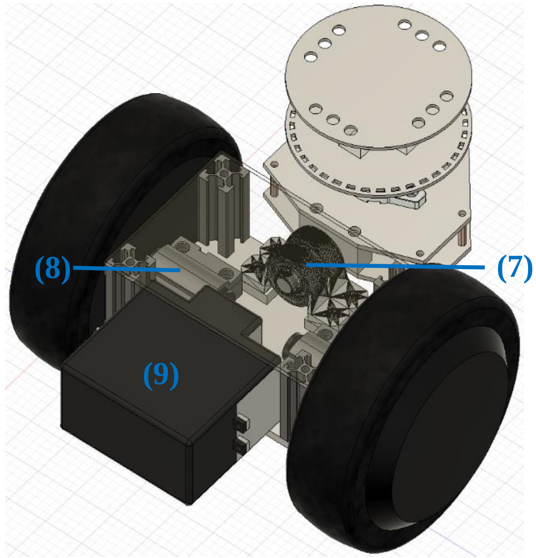


Figure A.3: MBot-One CAD model

Part	Component
(1)	Mounting plate
(2)	Dielectric Elastomers (DE) dampers
(3)	Optical encoder disc
(4)	FL000 pillow block ball bearings
(5)	36V battery
(6)	Brushless DC motor and wheel
(7)	P000 pillow block ball bearings
(8)	Motor mount
(9)	Electronics housing

Description	Quantity
Maximum Length	265 mm
Maximum Width	255 mm
Maximum Height	185 mm
Wheel Diameter	155 mm

Appendix D

Figure A.4: Inside the BLDC motor/wheel used

Appendix E

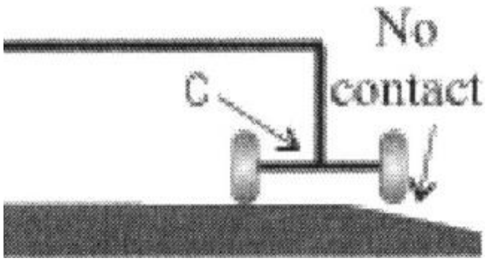


Figure A.5: ASOC module operation on uneven ground without passive suspension

Appendix F

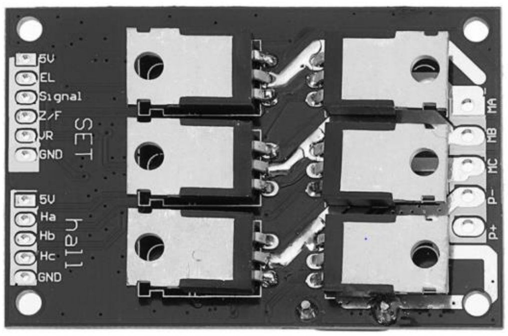


Figure A.6: Commercial BLDC motor with control pins

Pin	**Function**
5V	5V power
EL	Engage pin (on/off)
Signal	Number of steps moved by motor (input)
Z/F	Direction of motor rotation
VR	Varies the speed of the motor (speed varies linearly with voltage applied)
GND	Ground
Hall pins	Operate motor hall sensor
Ma, Mb, Mc	Corresponds to motor’s 3 phases
P+	Positive terminal for external power supply
P-	Negative terminal for external power supply

Appendix G

Details of sample	
Elastomer	3M VHB 4910 (1.0mm thickness)
Electrode	Carbon grease
Number of layers	10
Dimensions	2.5x2.5cm electrode, 3.5x3.5cm elastomer

Details of experiment	
Power supply	TREK Model 20/20C High Voltage Amplifier
Tested voltage range	4kV to 12kV
Electrical breakdown voltage	14kV
Equipment to measure height change of sample	Laser sensor

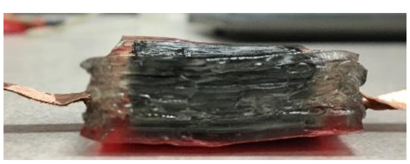


Figure A.7: Elastomer stack sample

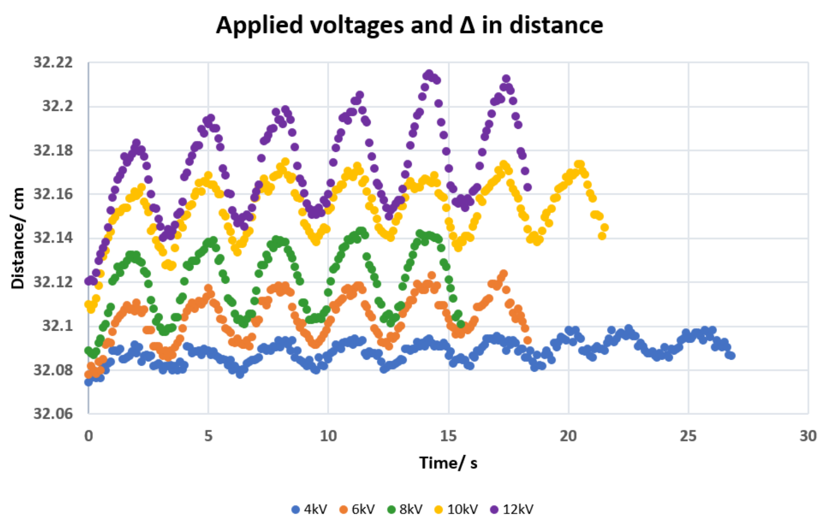


Figure A.8: Varying change in height observed with varying voltage applied