**WSP068 / WSP768 / WSD568 Mechatronic System Design Individual Coursework Assignment**

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# Task 1

A)

When looking at the Diagrams & problem statement, there are a handful of key requirements in addition to assumptions that can be made. Firstly, in terms of requirements for the positional sensor, there needs to be an understanding of the range & accuracy that is able to be recorded when considering the horizontal/vertical displacement. The range must be +/-100mm on both axes, with an accuracy of 0.2mm maintained throughout this range. Secondly, another key requirement would be the sensor system must be able to also consistently monitor the motion of an input signal with a bandwidth of 1Hz without substantial latency or distortion. This indicates the need for a sampling rate considerably above the input frequency (of 1Hz stated by the problem) to guarantee precise capture and prevent aliasing problems (an error commonly found when a signal is above a Nyquist freq.).

Taking all these factors into account, there are still some assumptions that could be argued that have influenced the thought process behind these considerations. Firstly, and most glaringly, there is an overlaying assumption that the table the sensor is based on will always predominantly be moving with the +/- 100mm range. In this same sense, it is assumed that anything higher or lower will be caught within the 0.2mm accuracy range, and anything anomalous, will be negligible thus, not worth considering.

Furthermore, there is an assumption that external factors to the sensor experiment will not in any way influence the operation of the machine. This includes but is not limited to factors such as the usage of a stable indoor lab environment with controlled climate, the absence of electromagnetic interference, the presence of appropriate mounting points (rigid & stable installation) and cable management solutions, sufficient power supply, and the ability to perform regular maintenance and calibration. These factors are crucial because they have a direct impact on the selection of sensor technology and overall system design, as well as establishing reasonable bounds for the operating circumstances in which the measurement system must work consistently.

So to summarize, the main key requirements for this position sensor concern:

1. The Accuracy of sensor to be within 0.2 mm (both axes)
2. The range to be +/- 100 mm in both directions (x/y)
3. The bandwidth of the sensor to capture a 1 Hz sinusoid motion without distortion
4. The use of a 1000kg table, must mean there could be electromagnetic interference which has to be considered in the overall selection process of a sensor

Assumptions:

1. Motion only being +/- 100m & 1Hz is the only frequency present (at Sine)
2. No Issues Environmentally/experimental contamination
3. Compatibility measurement systems from an analog & digital perspective
4. Setup of sensors is correct, and alignment is not faulty (And maintained to a correct level)

B)

During this portion, there will be an identification of key tools/technologies that could be integrated into the sensor simulation table, ensuring that the key requirements listed above are met and that the assumptions identified are followed. The list of recommendation and identified technologies are as follows:

1. LVDTs (Linear Variable Differential Transformers)
2. MLPS (Magnetostrictive Linear Position Sensor)
3. Laser-Based Displacement Sensor

The Primary choice of LVDTs being selected, was due to a hand ful of characteristics that found itself lined up with the requirements of the needs of the earthquake sensor. A LVDT itself, is an electromagnetic transducer with the primary purpose of converting motion into electrical signals. It has 3 components which are made up of a central coil and 2 coils either side running parallel. It uses the positional changes in a magnet central core to produce an output voltage which is directly comparable to the core's position, therefore allowing a signal to be read when the table begins to shake under pressure. Taking this into account, LVDTs allow for an extremely accurate (within a sub-millimeter range) reading, which is required as per the specification. Due to the nature of being used to convert motion into signals that can be read & analyzed, it is worth noting they have an increased resistance to vibration and mechanical stress (due to their inherit robust nature) as a result, meaning that the requirement of +/- 100mm range, can be handled without any serious difficulties whilst also simultaneously reading a 1Hz sine wave (meeting the bandwidth requirements).

Moreover, Magnetostrictive Linear Position Sensor (MLPS), is another type of sensor that can be used should the consideration of LVDTs not be valid. A MLPS sensor comprises ferromagnetic properties designed to change shape when in contact with a magnet field. Generally speaking, it works by transmitting an electrical-based pulse through a rod located on the MLPS, inducing what is referred to as a twist. This twist generates a wave that propagates to the rod's terminus at a predetermined velocity, and by measuring the duration for this wave to arrive at the end, we can precisely ascertain the position of the magnet. Similarly to the LVDT, the durability of this particular sensor can be made to withstand a good level of vibration found within earthquake simulation, whilst also meeting the requirement of 0.2mm. It does also have an advantage over the LVDTs, whereby installation and maintenance overtime is seem to be relatively simpler due to less mechanical parts, and are a lot more forgiving when it comes to mounting

Finally, the use of a Laser-Based Displacement Sensor, has also been mentioned for the purpose of this earthquake based analysis tool. These particular types of sensors are able to provide accurate readings (within the requirements), but tend to have more issues in terms of durability. Assuming my assumptions are correct about the resilience needed, the vibration, strict alignment prerequisites, and elevated costs render them suboptimal for earthquake simulation settings due to the damage that could occur at any given moment. The only way to potentially counteract this deficiency, would be to implement additional environmental protection measures, hence complicating the installation and maintenance processes, whilst increasing the overall cost to conduct the experiment in comparison to other measures.

C)

Based on the research on manufacturing parts undertaken, a particular piece of equipment has been retrieved that can be used within the earthquake sensor, this being the Measurement Specialties DC-EC Series LVDT, in particular the DC-EC 5000 spec model (part number: 02560988-000, ±5 inch LVDT)[1]. The main argument to wanting to use this particular LVDT, is that it doesn't compromise any factor relating to reliability, and is still capable of pushing out upper class performance. This is due to its robust steel housing and construction, which also features things like a magnetic shielding unit.

In terms of range, the DC- EC 5000 itself is capable of offering an extended measuring range of +/- 127mm (approximately 5 inches), which is noticeable, above the necessary +/- 100mm, hence providing advantageous safety margins and future adaptability for the earthquake simulator should any parameters need to be adjusted.

In addition to this, in terms of accuracy, the sensor uses a sensitivity of approximately 2.0 Volts Direct Current per Inch (VDC/Inc). This essentially means that the sensor is so accurate, that it should actually capture data below the 0.2mm specified handicap (or allowance range). Moreover, Measurement Specialties boasts that the DC-EC 5000 has a stability factor of 0.125% of full scale output as well as a ripple specification of 25mVRMS, which means that any noise captured due to the dynamic movement will be minimized, and data will be clean for usage. This is further emphasized

The last technical requirement revolves around adhering to the bandwidth requirements of 1Hz (Sinusoidal wave). Based on the technical information available from the spec sheet, if we were to use Figure 2 of an example input signal on the sensor, the DC-EC 5000 LVDT is capable of achieving numerous readings within just a second of the 1Hz wave. This is because if has a 200 Hz frequency response @ -3dB, meaning that in just a second, 200 samples/measurement points are collected for analysis. This makes it so that for every second or minute the table is running, not a singular vibration will be missed, ensuring that the most complete amount of results are collected.

Some other considerations, as briefly mentioned, would be the construction of the sensor itself. The dimensions of the sensor are 511.8mm (length) at 325g, core cetner of (242.1mm) at just 17g and 157.5mm (core length). The relatively low overall mass is crucial for the usage in the context of an earthquake simulator, as the lesser weight mitigates the sensor's inertial effects on the table when movement is applied, thus preventing the measuring system from affecting the motion it is sent to initially assess. Not only this, but Measurement Specialties provide bespoke mounting equipment for their sensor technology, allowing them to be easily applied to whatever context required, in this case, earthquake analysis.

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[1]https://www.te.com/commerce/DocumentDelivery/DDEController?Action=showdoc&DocId=Data+Sheet%7FDC-EC%7FA2%7Fpdf%7FEnglish%7FENG_DS_DC-EC_A2.pdf%7FCAT-LVDT0032

## Task 2

A)

Before beginning the calculations, some assumptions can be made:

1. The input wave is only Sinusodal
2. Gravity is the only force acting upon the vertical actuator
    a. There are no other forces (Friction/Air Resistance)
3. The center of mass, is placed directly in the middle of the table (1000kg)
4. The body of the system is considered rigid
5. The Frequency of the system is always at 1Hz
6. Maximum displacement at any given moment is +/- 100mm

$A = 100mm / 0.1m$
$f = 1Hz$
$m = 1000kg$
$g = 9.81 m/s^2$

Angular freq

$\omega = 2\pi f$
$\omega = 2\pi f \times 1$
$= 2\pi \; rad/s$
or
$6.283 \; Rad/s$
or
$39.478 \; rad^2/s^2$

Max Acceleration

$a(t) = -A\omega^2 \sin(\omega t)$
$a = A\omega^2$
$= 0.1 \times 39.478$
$a_{max} = 3.9478 m/s^2$
$\approx 3.95 m/s^2$

As can be seen in the workings above, the problem is first divided in the variables derived from the specification obtained from Task 1. The next part of the problem has us addressing the max acceleration, which can be found out by getting the angular frequency when checking the rate of

Horizontal

$F = ma$
$F_{hor} = 1000 \times 3.9478$
$= 3947.8 N$
$\approx 3948 N$

Vertical

$a(t) \quad a_m = 3.9478 m/s^2$
$F = m \times [g - (-a_m)] = m \times (g \times a_m)$
$F = 1000 \times (9.81 + 3.9478)$
$= 1000 \times 13.7578$
$= 13{,}757.8 N$
$\approx 13{,}758 N$

change within the sine function.

From that point, we can use Newton's second law of motion to substitute the values obtained from the calculation of angular frequency and max acceleration. This leaves us with a final **Horizontal** Maximum force of **3947.8N** & **Vertical** Maximum force of **13,757.8N.**

B)

**Variables**

$P = 200\text{bar} / 2 \times 10^{7}\ \text{Pa}$

Horizontal $= 3,947.8\text{N}$

Vert $= 13,757.8\text{N}$

$$F = pA$$

$$A = \frac{F}{p}$$

**Vertical**

$$A = \frac{13,757.8}{2 \times 10^{7}} = 6.87892 \times 10^{-4}\ \text{m}^2$$

or

$$\underline{6.87892\ \text{cm}^2}$$

**Horizontal**

$$A = \frac{3,947.8}{2 \times 10^{7}} = 1.97392 \times 10^{-4}\ \text{m}^2$$

or

$$\underline{1.97392\ \text{cm}^2}$$

i)

Task 2B(i) focuses on examining the hypothetical instance that the supply pressure of a set of hydraulic actuators is 200bar, of which the area needed to create this force in the actuators must be derived. Starting from the left most figure, key information has been written out to make note of the pressure (with conversion into Pascals) as well as the horizontal/vertical maximum forces obtained from task 2A. It is also worth noting that the formula that was used is F = PA, which is denoted to find the force but reformed to find A (Area), which in this case was referring to the actuator area.

The resultant for both vertical & horizontal can be seen in the second figure, with Vertical Area coming out to **6.87892** $^{2}$ or **6.87892 cm**$^{2}$ & Horizontal area is **1.97392 x 10**$^{-4}$**m**$^{2}$ or **1.97392 cm**$^{2}$

**Key Info**

Range(Amp) $= 100\text{mm} / 0.1\text{m}$

Freq $= 1\text{Hz}$

$\text{Area}_H = 1.9739\ \text{cm}^2$

$\text{Area}_V = 6.8789\ \text{cm}^2$

Ang Freq$(\omega) = 2\pi f = 6.2832\ \text{Rad/s}$

$$\underbrace{Q}_{\text{Flow Rate}} = \underbrace{A}_{\text{Area}} \times \underbrace{V}_{\text{Velocity}}$$

Flow rate Formula

ii)

Task 2B(ii) examines the systematic flow rate required in an attempt to achieve the velocity needed for both actuators to be operating simultaneously. Firstly, the key information is laid out which includes the range of the actuators (in terms of their amplitude motion), the frequency of that motion, in addition to the areas of both actuators as figured out in the previous section.

It is worth also pointing out, the formula:

$$Q = AV$$

This formula is the flow rate, which is going to be used twice per actuator, then combined (for a total).

Velocity

V

$$V = A\omega$$
$$= 0.1 \times 6.2832$$
$$= 0.62832\ m/s$$

Horizontal

$$Q = 1.9739 \times 10^{-4} \times 0.62832$$
$$Q_H = 1.24026 \times 10^{-4}\ m^3/s$$

Vertical

$$Q = 6.8789 \times 10^{-4} \times 0.62832$$
$$Q_V = 4.32219 \times 10^{-4}\ m^3/s$$

Total

$$Q_T = Q_H + Q_V$$
$$= 5.56245 \times 10^{-4}\ m^3/s$$

Firstly, the velocity of the sine wave must be determined by taking the amplitude of 0.1 & multiplying it by the angular frequency, which is our temporal rate of how a wave changes over time (figure on the left). . From this, 0.62832 m/s was observed as the rate of change, which will prove to be useful in now calculating the flow rate in each of the actuators. This is done by taking the previously noted formula and substituting our new figures, resulting in a horizontal rate of change of **1.24026x $10^{-4}m^3/s$,** and a vertical flow rate of **4.32219 x $10^{-4}m^3/s$.** When adding these together, our overall rate of change becomes **5.56245 x $10^{-4}m^3/s$.**

Flow → L/M

$$1\ m^3 = 1000\ L$$
$$\therefore Q_L = 5.56245 \times 10^{-4} \times 60 \times 1000$$
$$= 33.3747$$

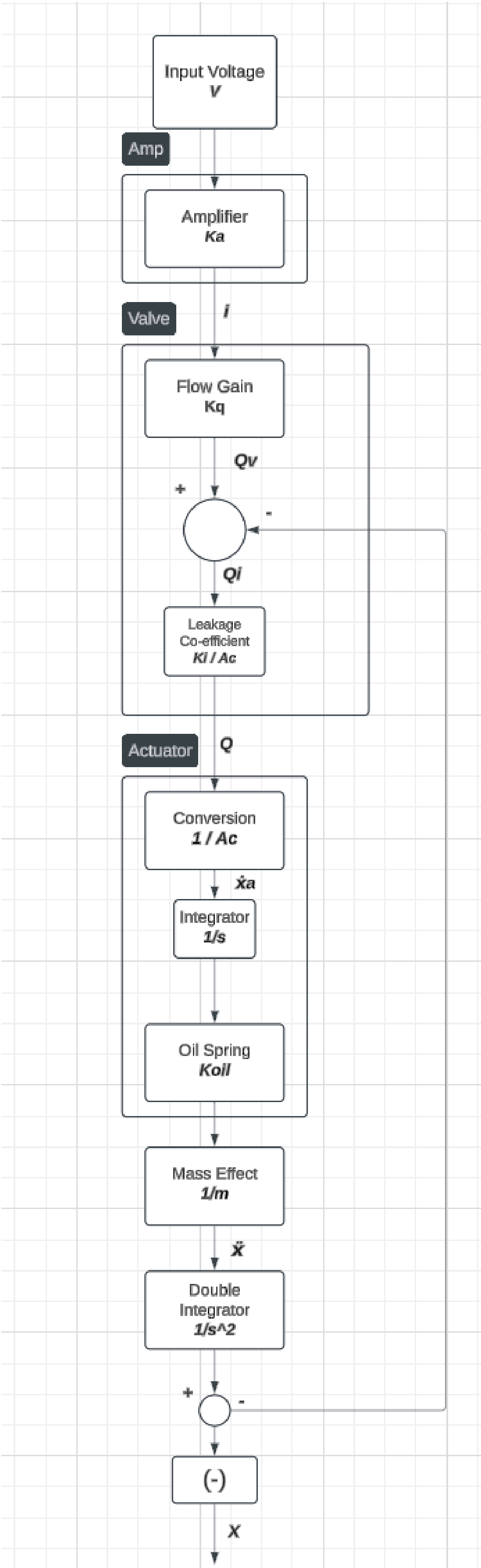
$$Q_T = \underline{33.37\ L/min}$$

or

$$0.55616667\ L/s$$

Finally, by taking the total maximum flow rate of both actuators combined to simulate them working in harmony with one another (**5.56245 x $10^{-4}m^3/s$),** we can convert this value into Liters per minute or per second (depending on the use case), which is illustrated in the figure just above.

The final answer derived is a total maximum flow rate of **33.37L/min** or **0.55616667 L/s** or **$2.00248m^3/h$.**




C)

The simple block diagram used to illustrate how the earthquake simulator functions as a system. Firstly, it should be noted that both actuators within this simulator are modeled in the same fashion, therefore it can be assumed that the simple block diagram produced can be used to analyze both horizontal and vertical actuation.

It initially begins by taking an input voltage (V), which is used in this instance to represent the sine wave of a 1Hz frequency. Once doing so, it is directed into a component known as the summing junction. This part of the circuit calculates the differential between the table's current location and where it should be, creating a new value, the error signal.

This error signal progresses within the valve subsystem where it is amplified to be integrated into the servo-valve (serves to help regulate the flow rate of the hydraulic fluid within the actuator). Because the system itself doesn't push all fluid to moving the actuator, the net flow is then calculated and subsequently subtracted (as an estimate), resolving in a value that details how much fluid is required to push the actuator into motion.

In typical hydraulic-based actuators, the change in fluid pressure allows for the movement of the physical system. The force exerted induces movement in the actuator, thereby causing the table to shift. The system accounts for the mass of the table and test structure, influencing the table's responsiveness to pressure fluctuations. The actuator's movement is accumulated over time to ascertain the table's new location.

The feedback loops seen in the basic block diagram (from the bottom back to the valve) provide the monitoring of the table's real time location. This feedback loop enables the system to continuously alter or minimize the erroneous signal through real-time adjustments. By modeling and regulating each component of the system the seismic testing apparatus can correctly emulate earthquake motions.

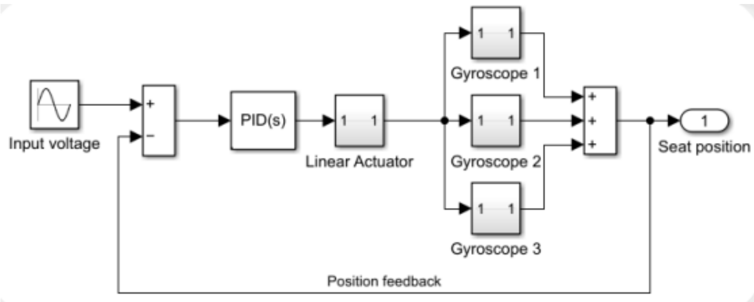
# Task 3

A)

In terms of the creation of the wheelchair, the main components have been identified and categorized for usage (actuators, sensor & control loops). Firstly, concerning actuators, the primary brand of actuator is the Festo electric linear actuator which has been used in the necessary role of slope compensation & the consideration of rider comfort. These particular types of actuators are rated at 24V DC with a stroke length of approximately 200mm and an actuation speed of 220 m/s. It should be noted that each of the actuators incorporates an additional motor, and servo drive, hence streamlining system design by obviating the necessity for external components. The actuators are configured in parallel arrangements, yielding a total force of 1400N (which should work out to approx 355N an actuator). The primary reason for this, is to create a sense of redundancy within the system, as by doing so, there is a reasonable level of being able to guarantee safe operation despite the failure of one actuator, preserving stability under failure situations with a tilt of up to 20 degrees. THese actuators have also been used conjunctionally with a selected brand of bike–based shock absorbers known as the RockShox Deluxe Ultimate RCT rear shocks, delivering active suspension management via servo-regulated damping according to terrain conditions (also aiding rider comfort). If we were to assume the passenger weight was 100kg (approx. 95th percentile of weight) and the tilting chair section at 70kg, then the Festo would be well within its requirements to be able to meet the requirement of a 40 degree actuation angle.

Sensors are another important factor when considering the design function of the wheelchair. The chair utilises a set of a couple of different types of sensors for the usage of tackles issues regarding navigation, terrain adaptation & general feedback. Firstly, the use of a gyroscope is a fundamental necessity due to the nature of the project, and in creating a solution that needs to be able to monitor the change in pitch, yaw & roll. The selected gyroscope is the Parallax Inc L3G4200D, which is a 3-axis gyroscope but works in combination with a ADXL345 accelerometer. The Parallax was used due to its ability to offer a range of adjustable (by the user), measurement ranges based on the suitable scenario which in this instance, can be set to ensure the different heights and terrains that one would face (like stairs or hills) are captured.

Furthermore, the Parallax is rated for an extreme level of temperature variance, allowing for regulator operation within the limits of -40°c to +80°C, which covers every possible scenario from a climate standpoint. On the other hand, the ADXL345 accelerometer is able to aid the gyro by creating an environment where 6 degrees of freedom are recorded and analysed. Since they both support $I^2C$ or SPI, they can both be put into a CAN bus configuration, meaning that there is significantly high levels of interplay between them that is uninterrupted or reduced chance of being disconnected. The CAN bus is also used in instances whereby high data transfer rates, reduced error handling & real time feedback control are favoured. For the purpose of this scenario, the gyroscope will be focused at a sampling rate of 800Hz. The main reason for this is it always for a high rate of measurement (approx every 1.25ms), and allows for the near instant detection of motion/tilt. This leads to the next sensor being used, which is an array of 3 LIDAR-Lite v3 laser based rangefinders, mounted at 45 degrees (on the front chassis). These particular types of LIDAR have an accuracy rating of +/- 2.5 cm at a range of 40m (500Hz), allowing them to very critically play the role of capturing changes in terrain, for example hills, bumps, stairs and so on.



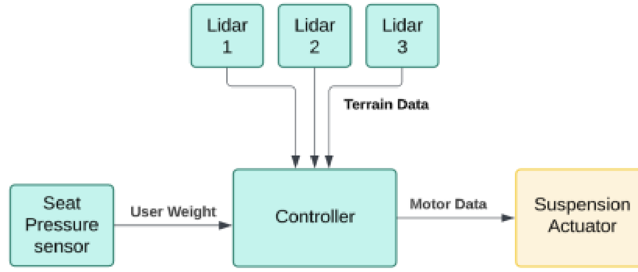
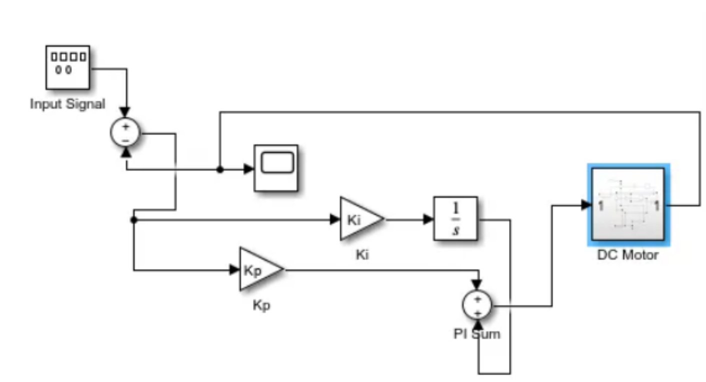



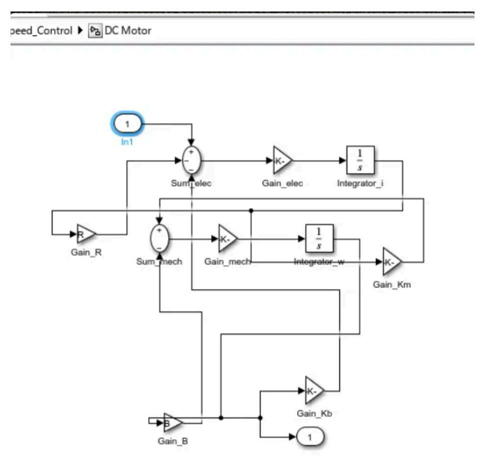

***Figure 1:*** *Slope Compensation Control Loop*

***Figure 2:*** *Suspension Actuation Control Loop*

Finally, control loops are the last crucial part of any system, as they aid in understanding how they are regulated and monitored to achieve desired outputs. In this case, control loops are used to manage the wheelchair to ensure that the target requirements are met and the wheelchair functions in the manner of which it was initially set out to. Based on figure 1, we can observe an instance whereby a control loop has been used to address the idea of slope compensation. It begins by taking a continuous voltage from the gyros, and sends it to the Festo actuators in an attempt to adjust the seat position, through the usage of a PID controller. The PID controller is also used in a control loop to ensure that acceleration is gradual or smooth and not jerky/instant. This logic can also be applied in figure 2, as we can see the use of a LIDAR array being fed into a control loop that adjusts the active damping/suspension of the wheelchair, to improve user comfort.

B)




The model type examined was to look at the creation of a DC Motor (right figure) connected to PID controller (left figure), with the purpose of limiting the speed of the wheelchair, the input signal of this particular dynamic model was a sine wave of 0.5 Hz, which in terms of performance, meant that a noticeable change to the motor’s speed could be observed.

Some assumptions were made in the sense that values assigned to components within and connected to the DC motor were assumed. Furthermore, there was an assumption between torque/current and the relationship between them was linear. The main reason for this was that it allowed for a more indepth look/concentration into the PID controller without having to worry about complexity issues. By also integrating a zero load torque, it should aid in isolating the PID’s performance at speed regulation without having to take into account the load variation conditions.

C)

Within mechatronics design, redundancy/fault management is the process of looking at ways to minimise the risk and usage of a particular system during its operation/use. In this instance, a scheme has been designed and implemented into the thought experiment of creating an operational terrain climbing wheelchair, for the purpose of reducing harm and risk to the operator/user while also ensuring that compliance is met with the appropriate standards (ISO7176/EN12183). The first point of redundancy integration is by implementing numerous actuators in the chair/suspension system. In the event of an actuator dilemma, the system is designed to allow and tolerate said issue while also maintaining a height of a 20° degree angle. This is done through PID controller-based adjustments, whereby the remaining actuators are able to adjust themselves and ensure the seat is still level. Furthermore, in the same instance of using a variety of components, a set of three gyroscopes or LIDARs (figure 1 & 2) are used in a voting format. This means that even if 1 of the 3 gyros were to fail, the system will still be able to detect and transmit accurate tilt sensor readings.

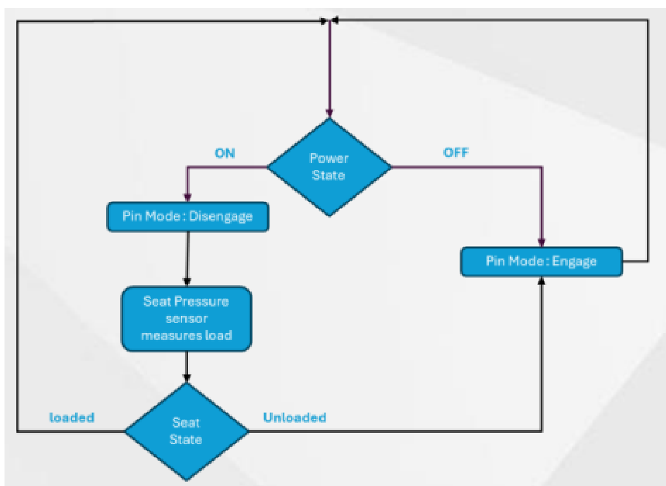



***Figure 3:*** *Flow Diagram on Pin Engagement*

More fail-safe implementation is apparent through the usage of pin engagement. As seen in figure 3, to demonstrate basic integration, the usage of an electromagnetic pin locking system (powered by a 24V solenoid) is used to disable basic functions of the chair while power is not running through the pin unless a certain criteria is met. Based on the figure, using the pin in tandem with a pressure sensitive seat/sensor array, means that the device cannot be engaged while a certain weight has been detected in the chair. As a side note, it is also worth mentioning that the engagement of the device is monitored user interface that can and should be relayed back to the user, to optimise hazard reduction.

Finally, the usage of a hierarchical response system in the form of a CAN bus network, can prove to be beneficial in the reduction of error materialization. This is done by splitting dilemma assessment into 3 main sectors of rise: minimal, moderate and significant. Minimal levels should look to allow normal-based operation with a slight reduction in performance, whilst more significant damage would have an emphasis on looking to initiate shutdown protocols, for example, reducing speed and directing the user to a safe pullover point (and alerting/contacting emergency services).