# Abstract

200-300 words written last

# Executive summary

1 page

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# Notes on Structure

The traditional thesis structure is broadly defined as:

* Introduction;
  + Background;
  + Scope; and,
  + Outline.
* Theory;
* Methods;
* Analysis;
* Discussion; and,
* Conclusions.

Due to the nature of the works competed in this thesis liberties were be taken to improve flow, clarity, and communication in general.

As per conventional structures, the project is introduced, and some background information relating to the context of the project is presented. From this the scope and focus of the thesis is derived and defined. Here deviation begins, rather addressing the project as a whole, which would require retention of swaths of unrelate information as one progresses through theory and methods, instead the project is broken down functionally into the major subsystems required for a successful project (as defined in the scope).

Within each of these subsections standard structure is employed. The purpose and context of the subsystem is explained, and the requirements for practical completion are detailed. From here a literature review is conducted as appropriate for each subsystem, explaining technologies or theory as needed. From this the specific methods, in design and implementation are detailed for each subsystem, e.g. the engineered design, and then the specific technology employed to implement the design. Finally, analysis is conducted on the outcomes of the subsystem in the context of the functional requirements defined.

The intention of this method is to allow for a consistent singular train of thought, where information on a system is presented sequentially (i.e. a single train of thought), rather than all information relevant to the thesis presented in order of type.

Once the subsystems are discussed, the same process (scope, requirements, theory, method, and analysis) is applied to the task of integrated all the major subsystems into a single supersystem. This section details the complete system and the performance of the exoskeleton developed. This section presumes knowledge of the subsystems but does not demand knowledge of their intricacies. The intention is that compartmentalising the details of the subsystems it is possible to discuss the design of the exoskeleton in general with brevity and clarity.

Finally, the results of the project are discussed, before the implications, recommendations, and conclusions of the project are discussed.

Readers primarily concerned with the outcomes of the proof of concept and thesis and not the specifics of how it was done, may find that reading 1 and then skipping to 17 (referencing the earlier sections of the documents as needed) as the most palatable method of consuming the document. Through this they may understand the projects context, what was done, and the results, without the dry technical details.

# Introduction and Outline

A powered exoskeleton, or exoskeleton, is wearable technology the amplifies and augments the pilot’s physicality. Through direct mechanical assistance via actuators, the pilot’s effective strength may be increased. By supplementing the strength required to complete a task the energy requirements of the task may be reduced; effectively increasing the pilot’s endurance. Possible applications for exoskeletons include: military operations, emergency & rescue, physical/manual labour, and medical applications.

Two major factors impact the viability of exoskeleton technology: power supply, and control. This thesis shall address one facet of the difficulties or exoskeleton control. Current exoskeleton control methods are inadequate due to mechanical constraints and the limitations of the control methods. Imperfections in mechanical design may result in a limited range of movement affecting the suits utility (e.g. A rigid spine in a confined space). Current methods of control use either force-based sensors or preprogramed movements. Finite sets of preprogramed movements are insufficient for dynamic environments and are only suitable for applications where the pilot is incapable of properly piloting the system (Charara, 2015). Force based methods encounter stability problems and may increase the exertion required to complete a task (Keller, 2016).

Instead this thesis will focus on the development of a novel power exoskeleton control method based on detecting the pilot’s position relative to the suit to maintain a constant offset; specifically focusing on the development of the controls and perception systems required to direct an exoskeleton.

An offset-based control system, by maintaining a constant offset from the user, may exist as a concentric outline (or *bubble*) of the user, mirroring their actions. Thus, to control the system the pilot simply needs to assume the desired position of the suit, and the suit shall mimic them. By mimicking the user’s actions, the suit is more intuitive that force based and preprogramed methods. The resulting system requires no physical contract with the pilot to control. With no physical contact required to operate the system the energy required from a pilot to complete a task with a load is effectively the same as completing the task with no load. Therefore, with any arbitrary load the user has the endurance to perform the task as if there no load at all.

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## Aim of Thesis

## Summary of Achievements

# Background and Problem breakdown

## Prior Art

Exoskeleton technology began in 1890 (United States of America Patent No. 440684, 1890), with Nicholas Yagin, with the development of a passive device that used compressed gas to assist in human movement, see Figure 1: Assisted-walking Device (Cybernetic Zoo, 2010).



Figure : Assisted-walking Device (Cybernetic Zoo, 2010)

However, it was not until the 1960s that the first attempt at a practical power exoskeleton was developed. The Hardiman (Keller, 2016) shown in Figure 2: G.E. Hardiman I Exoskeleton (Cybernetic Zoo, 2010), created by General Electric, was ground-breaking but non-viable due to its extreme weight (double its maximum load) and control problems. The suit, when used as a complete system instead of in parts, was subject to dangerous violent uncontrolled movements and the master-slave control system suffered debilitating lag.



Figure : G.E. Hardiman I Exoskeleton (Cybernetic Zoo, 2010)

Prospective uses for exoskeletons usually involve a scenario where a human user may require the strength and endurance of a machine, but circumstances result in wheeled vehicles are undesirable. Examples of possible applications include:

* Military Operations: operators are required to carry head loads over longs distances, lift large weights, and operate in dynamic and unruly conditions. Difficult terrain, heterodox environments, and general disarray result in heavy machinery often being unsuitable for certain circumstances. From urban to jungle operation exoskeletons provide possible utility.
* Rescue and evacuation missions: Rescue operations feature similar constraints to military operation with the additional concern of environmental hazards and structural collapse. In the event of a fire or chemical incident, the safety equipment and tools can be large, heavy, and cumbersome; exoskeletons can alleviate some of this burden. Where structures are damaged or collapsed an exoskeleton can provide the extra strength required to save a life,
* Medical Systems: When amputation, age, or illness results in an individual suffering from reduced mobility and strength exoskeletons present exciting opportunities to compensate for their pilot’s impediments.
* Construction & Physical Labour:

These applications represent some of the broader more immediately uses for exoskeletons, neglecting the role of specifically designed exoskeletons for niche tasks: shock absorbing legs for parachutes/paratroopers, self-propelled underwater diving suits, etc.

Since the Hardiman, exoskeletons have been plagued by the same two major problems that have prevented their use in real world applications: power to weight ratio/power supply and control. The following outlines current developments in exoskeleton technologies.

### HULC

The Human Universal Load Carrier (HULC) is battery-powered lower extremity exoskeleton initially developed by Berkeley Robotics and Human Engineering Laboratory, before entering an exclusive licensing agreement with Lockheed Martin in 2009 (Axe, 2012). The system uses hydraulics to amplify the pilot’s knees and hips while supporting a load of 90kg. Designed for military applications it claims six hours of battery and uses force-based sensors for control.

The HULC was abandoned as” it proved impractical, exhausting users instead of supercharging them” (Cornwall, 2015) and has been succeeded by the TALOS project (Cornwall, 2015).

### EskoGT

In 2010 the original developer of the HULC, Esko Bionics revealed the Exoskeleton Lower Extremity Gait System (eLEGS) (Charara, 2015). With a maximum battery life of 6 hours and maximum gait of 3.2m/s (Charara, 2015), the system uses pushbuttons and force-motion sensors for control. Specially design for medical applications, the exoskeleton uses preprogramed movements to aid the mobility of stroke and spinal injury patients.

The suit is ill suited for dynamic environments, with its finite range of movements prohibiting stairs and uneven surfaces. While the suit may assist those with “upper extremity motor function of at least 4/5 in at least one arm” (Charara, 2015), the suit is slower than a wheelchair and is not an improvement on standard human movement.

### Raytheon XOS Exoskeleton

The 2008 Raytheon XOS Exoskeleton developed by Raytheon is a full body exoskeleton that can support up to 23kg on each arm (Karlin, 2011). The suit uses force-based sensors for control. Despite claims that the exoskeleton would be ready for production by 2016, they have made no public comments on progress since 2011 (Karlin, 2011).

### Warrior Web

The Warrior Web non-rigid exoskeleton was first demonstrated at the 2016 DARPA Demo Day (Cornwall, 2015). Developed by DARPA, it used preprogramed commands to assist with the user’s ankle motions. However, it was unpredictable in uneven terrain, malfunctioned, and could not transition readily between a walking and running state (Cornwall, 2015).

### Hybrid Assistive Limb (HAL)

In 1997 Cyberdine unveiled the Hybrid Assistive Limb (HAL) (Cyberdyne, 2016). The HAL’s iterations include a battery-powered lower extremity exoskeleton and a full body exoskeleton (Cyberdyne, 2016). Through a combination of bioelectrical sensors and force sensors the HAL measured muscle contracts to trigger preprogramed movements.

The system has had mixed success, and despite applying for USA FDA approval in 2014, the HAL is yet to be permitted for use in the US (Cyberdyne, 2015).

## Preprogramed Control

Preprogramed control methods consist of a set of specific movements that are triggered in one way or another. HAL measures contractions in the arms of patients to trigger as the swing them back and forth to trigger left-foot right-foot walking motions. Warrior Web applies torque to the ankle of the user (assisting them walk) when movement is detected.

These systems are inherently limited in their utility. By having a finite or procedurally generated set of movements there will always be scenarios or circumstances where the set of movements is not applicable. In real dynamic environments (e.g. military, rescue & evacuation, and physical labour) dynamic controls are required.

As noted by Dunietz when using an exoskeleton with preprogramed controls, the ”human does try to join in the motion, the two get in each other’s way, cancelling out the gains for all but the most extreme disabilities.” (Dunietz, 2017) Though this we seem the limited applicability of preprogramed movements; in circumstances where the movement of the pilot is so limited and restricted (e.g. via disability) that any system is an improvement. For an able-bodied pilot preprogramed movements are ”a bit like being a marionette with four wires controlling my legs” (Cornwall, 2015) and inadequate.

## Force Based Control

Force based control systems use force applied to the internals of a suit to determine the users desired position. The force applied indicates the direction and magnitude of movement. Force based systems are often inadequate for practical applications due to the sensitivity of force input. Systems which are too sensitive may develop jitter, and lags between sensing and movement combines with physical inertia may result in the system applying force to the user, creating an unstable feedback loop. Systems with are insensitive are slugging and require the pilot to push and move against the suit. Using these systems can be sluggish, cumbersome, and exhausting to use.

As the only mechanism for detecting position for a force-based system is the user making contact with the suit misalignments in sizing can result physical dead bands when users are unable to touch the suit and the control system is effectively blind. Additionally, suits which maintain constant contact with asymmetrical body parts may interpret asymmetry as force input and therefore require constant active resistance from the user to control.

Finally, force-based systems do not distinguish between the force output of the system and the speed desired. If a user wishes to move quickly they must apply a large amount force to the system, if the suit encounters and obstacle this movement is then interpreted as a large amount of force applied to the object. There is no mechanism for quick safe movements.

For exoskeletons in dynamic real-world environments to be viable, responsive, and safe improvement on the existing force-based sensing methods are required.

## Proximity as a solution

Consider the following:

1. For controlling the suit, it may be assumed that the user is inside the suit during operation;
2. The users desired position for the suit may be treated as their personally bodily position;
3. Thus, the positional error between the desired configuration of the suit and the actual configuration of the suit is the difference between the configuration of the pilot and the configuration of the exoskeleton;
4. If the position of the pilot relative to the suit is measured and known, then the position of the suit relative to the pilot can be known; and,
5. Therefore, the suit can be controlled accurately (that is to say, error can be known at any time) by observing the position of the pilot relative to the suit; with no abstraction between measurement type (given in position) and desired state (given by position).

It is proposed to develop a proof of concept for an exoskeleton control system based on measurement of the pilot’s position/proximity the suit. By maintaining a constant offset from the user, the exoskeleton may exist as a concentric outline (or *bubble*) of the user, mirroring their actions.

Consider the following:

1. In a circumstance where the exoskeleton encounters an obstacle it is desirable to regulate and control the force output of the system;
2. It is desirable to decouple the control of force output and speed (a noted flaw with force-based control methods);
3. If the force output of the system is monitored by sensing its interactions with the environment, then the force output of the system can by regulated by then regulating the actions of it actuators; and,
4. Therefore, to ensure safe movement that does not apply undue for to the environment the force output of the system should be measured and regulated at external contact points.

It is proposed that for a position-based exoskeleton control system that the force output is directly measured (at contact points) to ensure safe and controlled operation.

Consider the following:

1. If the system applies force up to a safe maximum, then once that maximum is met then the exoskeleton will stop applying force to match pace with the user’s movement;
2. Under these circumstances the constant offset between the user and the system will not be maintained;
3. The user then may make contact with the internals of the suit;
4. It is possible to use the pilot continuing attempt to move in the direction of the opposing force as intent to increase force output of the suit;
5. By measuring the force applied by the user to the inside of the suit at contact points it may be possible for the user to indicate the desire for increased force output;
6. By measuring the force applied to external and internal contact points by the suit and the pilot respectively it is possible for the suit to operate with safe low force outputs which a pilot may override when increase force output is desired; and,
7. By using this system when the actuators are capable of strength beyond normal human capabilities, the pilot can effectively command and control superhuman strength in a safe and intuitive manner.

It is proposed to properly control the force output of the system the forces applied internally and externally to the exoskeleton are measured, and the force applied by the user to the internals of the suit are used to control the force output of the systems actuators.

The subsequent system in summary:

* Uses position sensors to determine the desired configuration of the exoskeleton from the bodily configuration of the pilot;
* Uses external sensors to regulate the force output of the system, maintaining a safe maximum; and,
* Measures force applied internally to determine the force output of the system.

The potential benefits of such a system are summarised as follows.

### Dynamic control

By mirror the movements of the user, with a sufficient mechanical design, the movements possible by the system is only limited by the capabilities of the pilot. Therefore, in any system which a human could navigate the system should be able to operate. Compared to preprogramed systems, it will be possible to navigate uneven terrain, switch contexts, and perform in unpredictable environments.

### Intuitive control

The system described shall provide more intuitive control relative to other solutions. If the pilot seeks to move the left leg of the system, they must simply move their left leg. If the suit makes contact with an object the suit will cease movement. If the pilot wishes to push the object, they simply need to push the object through the suit. The pilot may control the suit as they would their own body.

### Effortless operation

The system significantly increases the effective endurance of the pilot while requiring no exertion to use. Using the example of carrying a heavy load, the user to walk normally requires a set amount of effort. With no load applied to the described exoskeleton the action should require the same amount of effort. With a sufficiently strong system, the system may be loaded with any arbitrary loaded but the increased effort to walk for the user will remain zero. The suit effectively gives the operator carrying a load the endurance of an operator with no load. Note, the magnitude of this benefit increases as the load increases.

## Functionality Requirements

To determine the viability of position-based exoskeleton control and develop a proof of concept it is essential to define the required capabilities of such a system. The following outlines the requirements for a functional exoskeleton system:

1. The system must be capable of steady-state/static operation;
2. The system must be capable of dynamic and actuated operation;
3. The system must be capable of dynamic and actuated operation with non-regulated/imprecise action;
4. The system must be capable of dynamic and actuated operation with regulated action; and,
5. The system must be capable of dynamic and actuated operation with regulated action under real-time conditions.

Should the system be capable of achieving level 5 operation it can be said to be fully functional. To assess the system’s level of functionality specific test case are required which may be considered representative movements of the requirements of each level of functionality. These are outlined as follows in Table 1: Functional levels and associated movements, these movements are detailed further in 22.1.

Table : Functional levels and associated movements

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Functionality Level | Representative Movement | Position of Pilot | Position of Exoskeleton | Force Applied by Pilot | Force Applied by Exoskeleton |
| L1 | Standing | **🗸** | **🗸** |  |  |
| L2 | Squatting | **🗸** | **🗸** |  |  |
| L3 | Stairs | **🗸** | **🗸** |  |  |
| L4 | Sitting | **🗸** | **🗸** | **🗸** | **🗸** |
| L5 | Sprinting | **🗸** | **🗸** | **🗸** | **🗸** |

As seen in Table 1: Functional levels and associated movements, there are four main pieces of information required to control the system at all levels. From the required information it is possible to create a system that can demonstrate all levels of functionality. Note that every representative movement for the system can be completed using only the lower extremities. This implies that to develop a proof of concept for position-based control only a lower extremity exoskeleton would be required.

# Scope

## Proof of Concept

The purpose of this thesis is to develop some of the major subsystems for a proof concept for a position-based exoskeleton control system. As noted above in 9.5, to create a proof of concept for the system only a lower extremity exoskeleton is required.

### Task Division

Creating said proof of concept however, is beyond the scale and scope of a single undergraduate thesis. Instead, the task was to be divided amongst two students, who would complete subsystems independently before integrating their work. It was eventually determined that the most elegant and functional demarcation of tasks would be to divide the system according to determining the required actions and performing the required actions. As such one student would be responsible for determining the required action from the exoskeleton systems to perform as desired, and one student would create a system that was capable of performing said actions. Broadly speaking, one student would design and create the sensing/perceiving and control systems for the proof of concept, and the other would create the structural and actuation systems of the proof of concept. The point of integration between the two systems would be a communication system capable of transmitting the desired action from one side to the other.

This student, Samuel Williams, was assigned the perception and control systems.

As a matter of clarification, it is important to note that the terms: actuation system, control system, perception system, and structural system are descriptive terms for the approximate scope and manner of certain groups of subsystems. They are not prescriptive and should not be treated as such, e.g. the mechanical structure required to hold the force sensors in place is structural but is within the scope of the perception systems not the structural system.

### Required Systems

A full functional decomposition can be found in 11.

Based on the specific division of tasks and the demarcation devised the following major functional requirements where identified.

1. Detection of Pilots position relative to the exoskeleton (detection of the suit’s absolute position would be the responsibility of the actuation system)
2. Force application of the exoskeleton to the environment and the pilot to the exoskeleton
3. Control system for determining required action (torque) from actuation system for correct operation
4. Communication from control & perception software to actuation system

### Inclusions (In Scope)

The commissioning of the following was considered within the of scope and the project:

* A lower extremity exoskeleton;
  + This includes feet, shins, thighs, and waist.
* Systems required to perceive the position of an exoskeleton pilot relative to the exoskeleton;
  + This includes the hardware, firmware, software, and mechanical structure required.
  + This is limited to detection of the position of the femur, tibia, and foot (treated as a singular entity). This does not include the detection of the position of individual toes or the internal actuation of the foot.
* Systems required to perceive the force applied by an exoskeleton pilot to an exoskeleton;
  + This includes the hardware, firmware, software, and mechanical structure required.
  + This is limited to the detection of force application at the soles of the feet and the rear of the pilot, zones required for the representative movements.
  + This is limited to a rigid sole without actuation, i.e. the foot may move and bend at the ankle but shall not be treated as flexing at the ball of the foot.
* Systems required to perceive the force applied by exoskeleton its environment;
  + This includes the hardware, firmware, software, and mechanical structure required.
  + This is limited to the detection of force application at the soles of the feet and the rear of the pilot, zones required for the representative movements.
  + This is limited to a rigid sole without actuation, i.e. the foot may move and bend at the ankle but shall not be treated as flexing at the ball of the foot.
* Controls theory required to determine the desired position of the exoskeleton; and,
  + This is limited to determining the desired torque and angle of the actuation systems.
  + This does not include determining power, voltage, or current requirements for actuators.
  + This does not include determining control inputs (e.g. pulse width modulation duty cycles) for the actuation systems.
* Communication systems required to relay system readings and desired actions between actuation system and controls system.
  + This is limited to creating an input and output connection for interfacing with the actuation & structural system via a common protocol.
  + This does not include the implementation of a communication protocol for the student responsible for the actuation & structural systems.

### Exclusions (Out of Scope)

The following tasks were considered out of scope and where excluded from the project:

* Commissioning of the torso, head, or upper extremities of an exoskeleton;
* Commissioning of actuation and structural systems required to support and actuate a lower extremity exoskeleton;
* Measurement of actuator positions or absolute exoskeleton position;
* Measurement of velocity, acceleration, or torque of any section of the exoskeleton;
* The development of an exoskeleton capable of supporting additional loads, i.e. carrying weights beyond those required for demonstration of proof of concept;
* There was no compensation for the flexion and distortion of body parts, e.g feet;
* Addressing power consumption problems, power-to-weight ratio problems, or price problems associated with exoskeletons;
* Actuation points (hip, knee, ankle) where constrained to 1 degree of freedom (DOF); and,
* Anything not in scope.

## Variations

The original proposed scope did not include the creation or design of any actuations, or the interfacing between the control and perceptions systems and the systems actuators. As the project progressed it became apparent that the mechanical/actuation section of the project would not be completed in time for proper operation and that to properly develop and demonstrate the functionality of the controls and perception system a testing rig would be required. As such, the original scope of the project was extended to include the design and create of a simplified actuation system capable of refining, testing, tuning, and demonstrating the controls and actuation systems.

Consequentially, a fifth major function requirement was added to the system:

1. Development of actuation system sufficient to demonstrate attainment of other major function requirements.

### Inclusions (In Scope)

The following was considered within the of scope and the project:

* Commissioning of actuators and mechanical structure required to demonstrate functionality of position detection systems;
* Commissioning of actuators and mechanical structure required to demonstrate functionality of force detection systems;
* Development of motor interface and power systems required to control actuators in the desired fashion.

No new exclusions were added to the project.

# Functional Decomposition

The system defined by the scope, see 10, was decomposed into its major function requirements as seen in 10.1.2. Functional decompositions were then completed for the major subsystems in their respective sections (see 12, 13, 14, 15, and 16). This section outlines that major function requirements of the system.



Figure ; System Decomposition

As seen in Figure 3; System Decomposition, he ultimate goal of the project is that all times the lower extremity exoskeleton will be in the desired position. This may be accomplished by constantly observing the differences between the current state of the system and the desired state of the system and then changing the current system accordingly.

To observe the desired state of the system the position of the pilot and the force applied by the pilot to the exoskeleton must be known.

As seen in figure kt, the position of a straight linear rod of a fixed length can be described by the relation of a point on the rod (as an angle) to a fixed rotational axis and origin. By observing the angle of a rod relative to an axis we can know the orientation of said rod. Therefore, to determine the current state of the pilot it is possible to observe the location of each limb segment (treated as a straight rod) in relation to a fixed rotation axis.

If the rotational axis of the actuation points of the exoskeleton alight with the rotation axis of each limb segment (assuming the hip, knee, and ankle may be treated as 1 DOF hinges) then the position of each limb in relation to the actuation point may be used to determine the position of each limb. By observing the position of the pilot’s limbs in relation to the suit, it is possible to know where the pilot is positioned (assuming the position of the suit is known).

As stated in 9.4, the pilot may apply force to the internals of the exoskeleton to indicate the desire to increase the force output of the suit. As a result, the force applied to the internals of the suit must be measured. For the representative motions required for a proof of concept; contact is only required with the ground and a seat, therefore the only locations where force output is required is the rear and the soles of the feet. Only knowledge of the force applied to the internals of the suit at contact points is required to maintain control.

By observing the actual state of the exoskeleton, it is possible to determine the changes required to approach the desired configuration of the exoskeleton. The force/torque output of the actuators of the system is consider out of scope, and the position of the actuators and the absolute position of the suit is considered out of scope. However, the force applied by the system to its environments is within scope and must be determined to identify if force output of the exoskeleton should be changed.

For the representative motions required for a proof of concept; contact is only required with the ground and a seat, therefore the only locations where force output is required is the rear and the soles of the feet. Only knowledge of the force applied to the externals of the suit at contact points is required to maintain control.

In order to determine the action required of the system once the state of the pilot and the state of the exoskeleton are known the kinematics of the suit and the system response in a given state must be known.

To communicate between devices and between the actuation and perception/controls systems it is necessary to transmit messages in a predefined format.

# Subsystem One: Relative Position of Pilot

This section details the analysis, design, implementation, and results of the subsystem responsible for the perception of the position of the pilot relative to the exoskeleton.

## Definition and Requirement

The overarching purpose of subsystem one (SS1) was to detect the position of the pilot relative to the position of the exoskeleton in real time. This may be accomplished, as noted in 9.4, by measuring the position of limbs in relation to fixed rotational axis on suit.

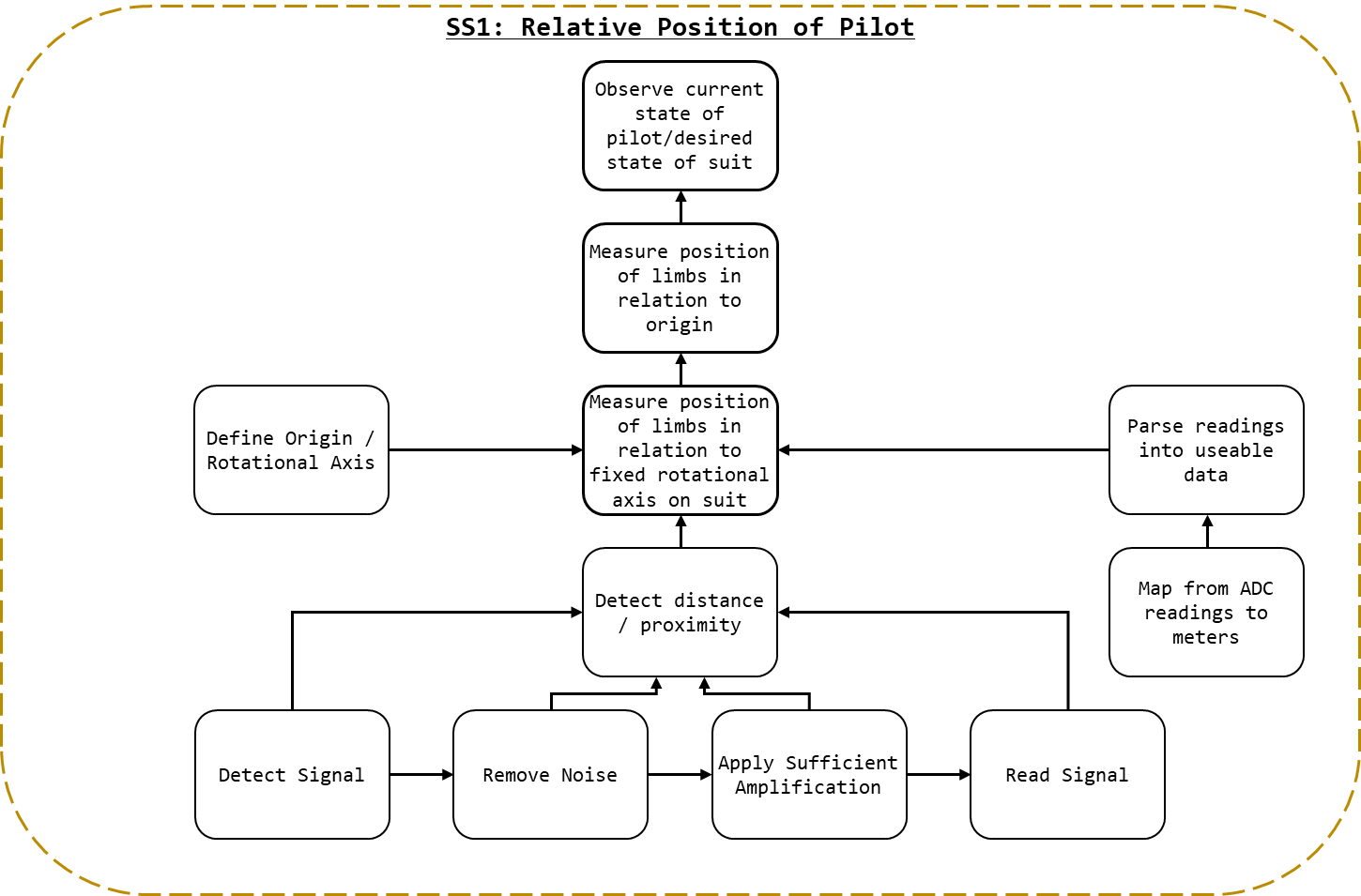


Figure : SS1 Breakdown

As detailed in Figure 4: SS1 Breakdown, to measure the position of limbs in relation to fixed rotational axis on suit:

* a fixed rotational axis must be defined;
  + this implies a fixed point where readings can be taken, as such, a mechnism for fastening the detection system must be devised.
* the position/distance must be measured; and,
* the measured distance must be parsed from raw values into useable data.
  + Functionally, this is the process of deriving the function that maps raw analogue voltage values to distance.

The process of measuring the distance will ostensibly entail:

* detecting a signal; the specific type will depend on the techonlogy selected (e.g. IR light, ultrasonic waves, magnetic field strength, etc);
* removing noise from the detected signal; ostensibly through the use of a filter;
* amplifying the cleaned up signal into a range suitble for reading; and,
* reading the signal, ostensibly with an ADC, into a format that can be parsed by the control systems.

## Background and Prior Art

The process of defining the fixed rotational axis and parsing readings into distance values are dictated by the system and are less subject to variation and subjectivity. Instead, the focus on researching prior art for SS1 was determining the most appropriate mechanisms for detecting distance. Additionally, research was conducted on appropriate filtering and amplification methods. The requirements for reading the signals synthesised are outlined, but the selection of a microcontroller for interfacing with all five subsystems is detailed in 17.

### Perceiving Distance

This section details many of the technology considered for perceiving the proximity of the pilot’s limbs. The sensor types given the most serious consideration are detailed here, with additional sensors types considered found in 22.2.

#### IR Transceiver

Infrared light, or IR, is a form of electromagnetic (EM) radiation general not visible to human eye’s (Lynch & Livingston, 2001). The wavelength of IR is typically defined as ranging from 700 nanometres (frequency 430 THz) to 1 millimetre (300 GHz) (Liew, 2018). IR is emitted by the sun, artificial lighting, fires, as thermal radiation from objects (and animals), and from IR emitters (American Technologies Network Corporation, 2018).

The prototypical IR emitter is a light emitting diode (LED) composed to emit IR when power. They typically share a formfactor with standard LEDs and are often used in IR communication. To receive a signal transmitted via an IR emitter and IR received is used. IR receivers may take the form of a photoresistor configured for IR range light. IR emitters and receivers are often used in concert to transmits a message (via the emitter) and then receive it (via the receiver) (Future Electronics, 2018).

Like all EM waves, IR suffers from attenuation (Garbett, 2001). IR is also capable of being reflected off a non-absorbing material. As seen in figure kt, by emitting IR and measuring the intensity of the light reflected it is possible to determine the distance from the reflective surface and the emitter. This principle may be applied to determine the distance of an object from a transceiver (IR emitter/transmitter and receiver).

IR is an effective method of detecting range, in fact IR is often employed in LiDAR (Cracknell & Hayes, 2007). Assuming line of sight exists between the reflection point and the IR receiver there is no minimum range. Additionally, IR technology is small, affordable, and ubiquitous. Under ideal conditions an IR transceiver would be capable of perceiving the instance between an exoskeleton and its pilot.

Outside of ideal conditions complications with IR technology can occur. As noted above, IR is ubiquitous and is emitted by the sun, artificial lighting, and animals meaning that even if all undesirable frequencies (e.g. the 38kHz carrier signal from most IR remotes) where filtered from an IR signal noise may still exist. Under poor operating conditions an IR transceiver may be saturated with IR rendering it effectively blind. Additionally, variability in the reflective surface may result in IR being reflected inconsistently or not at all. Under these conditions mapping from signal intensity to distance may be impossible, as different surfaces will yield different signal intensities.

### Filters and Amplification

This section details the theory required for understanding the requirements and design of the filter and amplifier designed for the proximity perception system.

Filters are applied in order to remove noise from a signal, noise defined as “irrelevant or meaningless data or output occurring along with desired information” (Merriam-Webster Dictionary, 2018). An active filter is a filter that uses active components (e.g. operational amplifiers), rather than entirely passive components. Depending on the nature of the noise present in a measured input specific input ranges may need to be filtered (e.g. unwanted frequencies).

A low pass filter is a filter that permits lower frequency signals and filters high frequency noise, with a high pass performing the opposite function. In the case where a specific signal frequency is desired a high pass and a low pass filter may be combined to allow a specific band of frequencies to remain. This configuration is known as a band pass filter.

A common and useful electronic filter topology is the Sallen–Key topology. The Sallen–Key topology is an electronic filter topology that allows for the simple implementation for a second order filter. Seen in kt, a band pass filter may by implemented in Sallen–Key topology.



By performing analysis on the circuit depict in figure kt, it is possible to determine the system response of a Sallen–Key bandpass filter.

TALK ABOUT WHAT EQUATIONS WE GET AND HOW THEY CAN BE USED HERE

Kt kt kt

Amplification can be applied to signal to increase its intensity. Within the finite window that is inherent to all measurement mechanisms amplification may be used to increase or decrease the relative signal strength so that the area of interest aligns with the range of measurement. In the context of proximity sensing where the signal intensity may vary (e.g. IR range finding) it may be possible amplify the specific regions on interest. For example, for a signal that ranges between 0-5V for a range of 0-1m being read by and ADC (analogue to digital converter) with a 0-5V range, it may be possible to amplify the signal such that the 10-20cm range constitutes the entire 0-5V range received by the ADC.

## Approach and Execution

### Perceiving Distance

When considering the conditions of operation, the distance perception system was expected to take reading from shifting, rippling, flexing human body parts. Body parts which may be clothed, shaved, hairy, firm, or soft. Body parts with rounded uneven surfaces at close ranges.

The conditions of operation featured many unknowns and the specific approach selected for the actuators could not be known prior to selection of the proximity sensing method (the significant delays would have been untenable). As such, the possibility of acoustic noise in the actuation system or the environment in general could not be dismissed.

Given this understanding of the operating conditions, ultrasonic sensors were considered inappropriate for the creation of a robust design within the constraints of the project.

IR range sensing was selected as the approach for determining distance. The Vishay TCRT5000 - Reflective Optical Sensor with Transistor Output was selected for the IR range sensing (Vishay Semiconductors, 2017), see Figure 5: TRCT5000 (Vishay Semiconductors, 2017). As stated by the manufacturer “The TCRT5000 and TCRT5000L are reflective sensors which include an infrared emitter and phototransistor in a leaded package which blocks visible light. The package includes two mounting clips.” (Vishay Semiconductors, 2017).



Figure : TRCT5000 (Vishay Semiconductors, 2017)

The TCRT5000’s datasheet may be found in the attached documents as “TCRT5000 - Reflective Optical Sensor with Transistor Output.pdf”. The following circuit was used for the configuration of the TRCT5000s within the project, see Figure 6: TRCT5000 Topology, where **SIG** represents the output signal.



Figure : TRCT5000 Topology

A printed circuit board (PCB) would be created to which an IR transceiver, or emitter and receiver, could be mounted. The PCB would be designed as such that it would interface with external systems by only power and signal cables. Ideally, the IR PCB would be modular, and in the case of damage, simply replaced with another like it. This circuit board would feature the circuit in Figure 6: TRCT5000 Topology and the header depicted in Figure 7: IR Sensor Mount Header Topology.



Figure : IR Sensor Mount Header Topology

The PCB was designed in Altium Designer (16.1), the PCB schematic may be found in the attached documents under the designation “IR Sensor Mount” and shown in Figure 8: IR Sensor Mount PCB Depiction.



Figure : IR Sensor Mount PCB Depiction

The PCBs were fabricated and assembled as shown in Figure 9: Fabricate IR Sensor Mount PCB.

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Figure : Fabricated IR Sensor Mount PCB

### Filters and Amplification

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### Fixed Rotational Axis

The fixed rotational axis upon which distance measurements would be referenced was determined to be the hip, knee, and ankle joints where ostensibly the actuators axis were to be place. As noted in 14, this considerable simplifies the kinematics and controls of the system. However, as the size of the exoskeleton and the limb segments devised was dependent on the mechanical build by those responsible for the actuation system estimations where required for the majority of the project regarding the specific length of limbs.

While it was presumed the exoskeleton’s structural systems would be on the external sides of the pilot’s body, the mounts for the position detection system would be designed without specifies on materials or dimensions of the exoskeleton (these values would remain unconfirmed until exceedingly late within the project).

It could not be presumed that the exoskeleton segments would have free ends, so the system would need to be designed to be attached, firmly, to a rod of an arbitrary shaped cross section of an arbitrary size, without access to a free end. It was required that wobbling vibration, ro movement of any kind was to be minimised and the connection would be remove and reattached an indeterminant number of times. The connection needed to be fast, simple, and not so complicated to introduce risks of improper application.

Hose clamps were identified as a suitable fastener method. Screw/band (worm gear) clamps, see Figure 5: Hose Clamp(Bunnings, 2018), are reusable, can be applied to a rod of an arbitrary shape and size (with ranges), affix firmly, and may be attached quickly with a screwdriver.



Figure : Hose Clamp(Bunnings, 2018)

However, as the details of the proposed exoskeleton became available it was noted that the cross section of exoskeleton frame may have been as small as 5mm in diameter. A size below the range of standard hose clamps. Instead, cable ties where identified as an ideal fastener method.

Seen in Figure 6: Cable Tie (Computer Cable Store, 2018), cable ties, or zip ties are a form of typically plastic ratcheting strap. The can be affixed to a rod of an arbitrary shape and size, attached by hand, and are disposable. While a less permanent solution for an attachment mechanism compared to hose clamps, the were deemed sufficient for a proof of concept.



Figure : Cable Tie (Computer Cable Store, 2018)

To mount the measurement structure to the exoskeleton a plat was design that could sit flush to the frame. As seen in figure Figure 7: Mount Structure, the structure (black), could be mounted to the exoskeleton frame A. Seen from the side, gutters where placed (B) so cable ties could be affixed, while guard rails (C) ensured the cable ties did not slip or move during operation. The measurement structure and any auxiliary objects could be affixed at the surface of the plate (D) with counterbored sections (E) for nuts and bolts to be mounted while sitting flush with the surface of the exoskeleton.



Figure : Mount Structure

The component was created in Autodesk Inventor, as seen in Figure 8: Mount Structure (Single) CAD. Attached to this document full CAD files for all components can be found kt.

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Figure : Mount Structure (Single) CAD

To minimise the weight of this component and ease in manufacturing, the mounting plate was constructed via 3D printing, see Figure 9: Printed Mount Structure (Single).

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Figure : Printed Mount Structure (Single)

## Execution

### Perceiving Distance

TRCT5000

### Filters and Amplification

Sallen Key

### Signal Input

[0,5,S] – best practice

4 ADC

### Mounting the fucker

Process of Mapping

## Results and Discussion

### Perceiving Distance

### Filters and Amplification

### Signal Input

# Subsystem Two: Force applied by and to Exoskeleton

This section details the analysis, design, implementation, and results of the subsystem responsible for the perception of the applied by the exoskeleton to the environment and by the pilot to the exoskeleton.

## Requirements and Functional Decomposition

## Prior Art

## Solution

## Implementation

## Results

# Subsystem Three: Controls and Decision Making

This section details the analysis, design, implementation, and results of the subsystem responsible for determining the actions required by the actuation system.

## Requirements and Functional Decomposition

## Prior Art

## Solution

## Implementation

## Results

# Subsystem Four: Communications

This section details the analysis, design, implementation, and results of the subsystem responsible for communication between the actuation systems and the controls/perception systems.

## Requirements and Functional Decomposition

## Prior Art

## Solution

## Implementation

## Results

# Subsystem Five: Actuation Systems

This section details the analysis, design, implementation, and results of the subsystem responsible for interfacing and actuating actuators to demonstrate the functionality of the other major subsystems.

## Requirements and Functional Decomposition

## Prior Art

## Solution

## Implementation

## Results

# Integrated Exoskeleton

This system details the process of integrating the engineered solutions of the major subsections of the project. Then the final holistic system commissioned is detailed.

## Requirements and Functional Decomposition

## Prior Art

## Solution

## Implementation

## Results

# Results and Performance

# Recommendations and Further Works

## SS1

* Use hose clamps

## SS2

## SS3

## SS4

## SS5

## Exoskeleton

# Conclusion

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# Appendices

## Representative Movements

### Level One Functionality: Standing

To stand while the exoskeleton system is engaged requires the system to be capable of achieving equilibrium and control in a static environment.

Level one functionality demonstrates that for an instantaneous snapshot of operation that the system is capable of regulated operation. Note, level one functionality may also highlight the system’s ability to compensate for steady state error.

### Level Two Functionality: Squatting

Level two functionality requires level one functionality.

To squat while the exoskeleton system is engaged requires the system to be capable of control in a dynamic environment where the pilot is moving. A squat allows for the pilot to engage in motion at the stable pace of the exoskeleton, and as such may non-real-time operations.

Level two functionality demonstrates that the system is capable on a fundamental level of mirroring the pilot’s movements.

### Level Three Functionality: Stair Climbing

Level three functionality requires level two functionality.

To climb up stairs while the exoskeleton system is engaged requires the system to be capable of control in a dynamic environment where the pilot is moving while also applying force to the environment. However, should the system apply too much force to the environment the exoskeleton will simply lift itself off the ground, ultimately not requiring meaningful force regulation.

Level three functionality demonstrates that the system is capable of applying force to an environment.

### Level Four Functionality: Sitting

Level four functionality requires level three functionality.

To sit down while the exoskeleton system is engaged requires the system to be capable of control in a dynamic environment where the pilot is moving while also applying force to the environment in a regulated manner. If the suit applied too great a force to a seat, then it may damage the seat. If the system is incapable of allowing the user to rest on the system, it may result in uncontrolled behaviour. As the pilot sits the system should concede to the force applied by the seat, until the point at which the plot applies force to the upper thighs of the system.

Simply, if a suit is capable of sitting, it is capable of interacting with the environment without destroying. Level four functionality demonstrates that the system is capable of applying force to an environment in a safe and regulated manner.

### Level Five Functionality: Standing/Walking/Sprinting

Level five functionality requires level four functionality.

Presuming all prior levels of functionality are attained the suit should be capable of all required actions. However, to switch contexts and move between standing, moving, and running actions requires dynamic real time control. For an exoskeleton system to be truly viable, it is essential that context switching, and real time control are possible.

Level five functionality demonstrates that the system is capable of acting in a real environment and acts as a complete proof of concept for position-based control methods.

## Unsuitable Proximity Sensors

#### Ultrasonic Range Finders

Ultrasonic waves are sound waves with a frequency above the audible range of humans, approximately 20 kHz (Cutnell & Johnson, 1998). Ultrasonic waves, as seen in figure kt, can used for range finding by emitting an ultrasonic sound and recording the time for the wave to be reflected back. Ultrasonic range finders have been used as the autofocus in cameras, and motion detectors, and are the underlying technology for Sonar.

Ultrasonic ranger sensors have the advantages of (Gross, 2018):

* not being dependant on the lighting conditions and offering reasonably high resolution at short distances; and,
* using sound rather than light, ultrasonic range finders are adept at detecting clear or transparent objects.

However, ultrasonic range finders have limitations (Robomart, 2015):

* they feature a minimum effective range, preventing their noncontact use at close range;
* the transmission of ultrasonic waves is affected by temperatures, humidity, and airborne particles; altering the perceived distance;
* for accurate measurement they require a hard, flat, level surface directly opposite and perpendicular. Compared to the irregular shapes and the hair of the human form, they may be ill suited; and,
* they are effect by ambient acoustic noise. The operation of the exoskeleton itself (specifically actuators) may create sufficient noise to interfere with any ultrasonic range finding.

#### Capacitive Proximity Sensors

Capacitive proximity sensors act in the manner of a capacitor where one plate functions as an output or a switch (Thomas Publishing Company, 2018). Capacitive proximity sensors are effective in high precision applications and controlled environments; however, they are less effective at greater ranges. Given the possibility of large uneven surfaces, comprised of unspecified materials capacitive proximity sensors were neglected from further consideration (Thomas Publishing Company, 2018).

#### Inductive Proximity Sensors

Inductive proximity sensors operate by the induction of eddy currents in metals and similarly conductive materials (Keyence Corporation, 2018). Humans are not metals or similarly conductive material, and as such not suitable for range finding via inductive proximity sensors (Keyence Corporation, 2018).

#### Magnetic Sensors

Range finding is possible using hall effect sensors (Texas Instruments Incorporated, 2017), magnetometers (Jackson, Green, & Eisenbeis, 2017), and Magnetoresistive Sensors (Arrow, 2018). While future iteration of the exoskeleton may include proximity detection based on magnetic sensors, they all depend on magnets (permanent or otherwise) to generate a field to be measured. In keeping the spirit of the “*Bubble”* design of the exoskeleton, it was elected to avoid perception methods that require sensors to be mounted to the pilot, and therefore, all magnetic sensors were excluded from selection.

## Code

* Firmware in C
* MATLAB

## PCBs

## CAD drawings