THE UNIVERSITY OF QUEENSLAND

AUSTRALIA

METR4901 Thesis Proposal

# I Am Ferrous Man: Using Proximity Based Guidance for Exoskeleton Control

*Samuel Williams*
*43219667*

School of Electrical Engineering and Information Technology,
University of Queensland

*Dr. Paul Pounds*

University of Queensland

August 24, 2017

# Contents

# 1 Topic Definition

## 1.1 Context

An exoskeleton is a powered wearable machine that uses actuators to assist human movement (Exoskeleton Report LLC, 2017). Exoskeletons exist to reduce the metabolic cost and difficulty of performing a task or enable the user to perform tasks beyond their normal physical capabilities. Applications cited for exoskeletons include: medical applications, military operations, emergency and rescue, and physical labour. There are numerous exoskeletons in development and production that attempt to address one or more of these uses. Further information regarding exoskeletons, past and present, their applications, and flaws can be found in 2 Background

Three major factors hinder the adoption of exoskeleton technology: price, power supply, and bulky cumbersome control. This thesis shall attempt to address problems inherent to existing designs for control. The clunky behaviour of existing exoskeletons is a consequence of their mechanical design, which may place limitation on the user's range of motion (e.g. a rigid spine), and by the methods of control. Most existing exoskeletons use force sensors to detect when the user attempts of move, and the Hybrid Assistive Limb (HAL) uses bioelectrical impulses to detect when the user's muscles contract (Cyberdyne, 2016). However, force and muscle contraction are not optimal and merely proxies for the users desired position. A more detailed discussion of why force and muscle contraction are substandard input types may be found in 2.2 Design flaws and limitations.To improve the control of exoskeletons a control system that uses position, rather than force as an input would be necessary.

## 1.2 Objectives

The goal of this thesis is to engineer and construct a proof of concept for a novel exoskeleton proximity based control system. As seen in Figure 1, the system will use an array of proximity sensors to determine the position of the user and attempt to maintain a constant offset from their body, acting as a concentric silhouette of the user.

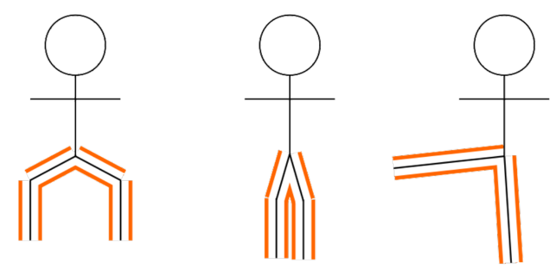


Figure 1: Proximity Based Control Exoskeleton

To show the efficacy of the technology a prototype will be commissioned to practically demonstrate the system functioning in default bases conditions and niche edge cases of difficulty. To qualify as successful prototype, and a proof of concept, the system must be able to perform the movements discussed in Table 1: Required Movements

Table 1: Required Movements

| Movement | Rational |
|---|---|
| Sitting | Sitting requires the suit to support its own weight and apply force, while not applying excessive force to the surface.<br>Additionally, it is a case of the user applying force to the internals of the suit |
| Standing | See sitting, but the user must also maintain balance. |
| Squats | See standing, but the suit must also actuate and match the user's movements |
| 1 Leg Stand | See squats, but the suit act asymmetrically under asymmetrical forces. |
| Walking | See 1 Leg Stand, but the suit must act at the user's speed. |

### 1.2.1 Project Partitioning

The physical prototype will be divided into two sections, mechanical and electrical. The mechanical design, will encompass the load bearing structure and actuation of the system. The electrical design, assigned to the author, includes the proximity sensors, auxiliary sensors, and control firmware. The control theory will be developed independently and concurrently by both sides of the project.

The electrical design will be responsible for sensing all system variables, excluding actuator outputs, and translating readings into usage data for the control software. While optimisation of the control system will be completed concurrently by those involved in the project, the author will be responsible for implementing the software framework supporting the controls solution of the system.

## 1.3 Scope

The project is focused on specifically the proximity based control system, and will make numerous simplifications and omissions in the interest of demonstrating the concept rather than attempting to create a fully functional whole-body suit. Most notable, only a lower extremity suit will be constructed, as all the desired tasks are solely dependent on movement below the waist. The list of simplifications, omissions, and liberties includes:

- Only the lower body of the suit will be constructed;
- Actuation points (ankle, knee, and hip) will be constrained to 1 DOF;
- The device will be powered by an umbilical power supply, rather than a mobile power supply;
- The device will not be designed to support additional loads;
- Flexion and extension of body parts (e.g the feet) will be omitted
- The movement of jumping will be omitted

### 1.3.1 In Scope

The following outlines what will be considered inside the scope of the thesis.

A proof of concept for a novel exoskeleton proximity based control system will be developed to perform the movements listed in Table 1: Required Movements, reliably and without malfunction. A working prototype will be completed no later than 14 May 2018 (to be ready for demonstration day). This portion of the project will produce all sensors required to observe the position of the exoskeleton's pilot, and desired exoskeleton configuration. Additionally, this portion of the project will produce all firmware, software, and controls required for the exoskeleton.

### 1.3.2 Out of Scope

The following will be considered outside the scope of the thesis:

- Anything that violates the listed simplifications;
- Measurement of actuator positions
- Measurement of actuator torque output
- Engineering and construction of the load bearing and actuated components of the suit;
- Engineering and construction of an actuated suit above the waist;
- Engineering and construction of a mobile (non-tethered) power supply;
- Addressing power supply issues;
- Addressing power to weight issues;
- Addressing price issues;
- Addressing mechanical limitations of existing exoskeleton designs; and,
- Anything not in scope.

# 2 Background

In 1890, Nicholas Yagin developed the first precursor to exoskeletons; a passive device that used compressed air to assist human movement. However, it was not until the 1960s that the first attempt at a practical power exoskeleton was developed. Created by General Electric, the Hardiman suffered numerous debilitating drawbacks: the suit weighed double its maximum load, attempts to use the entire suit in concert resulted in violent uncontrolled movement, and the master slave control system suffered from massive lag. Since the abandonment of the Hardiman development of exoskeletons has continued. Most exoskeletons attempt to amplify the capabilities of the human user in one or more of the following applications:

- Military: Exoskeletons may be used to enhance the strength and endurance of users, allowing them to operate for longer with greater equipment loads. Load bearing exoskeletons invite the potential for improved armour, equipment, and munitions.
- Medical: Exoskeletons can be used to compensate for physical disabilities and handicaps, and can be used for physical rehabilitation.
- Physical labour: Activities where physical strength and endurance is required but larger vehicles and machines are impractical have been considered potential avenues for exoskeletons. Rescue operations, warehouse workers, tradespersons, and construction workers may all benefit from exoskeleton technology.

## 2.1 Existing Technologies

The following outlines major existing exoskeleton technologies.

### 2.1.1 Human Universal Load Carrier (HULC)

In development since 2000 at Berkeley Robotics and Human Engineering Laboratory, before an exclusive licensing agreement with Lockheed Martin in 2009, the Human Universal Load Carrier (HULC) is battery-powered lower extremity exoskeleton. Designed for military applications, the HULC uses hydraulics to amplify the pilot's knees and hips, can support a load of 90kg (200lbs), and has a walking battery life of 8hrs. The HULC used force and motion sensors for control.

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

### 2.1.2 EksoGT

Esko Bionics, the original developer of HULC, in 2010 revealed the Exoskeleton Lower Extremity Gait System (eLEGS). Designed for medical applications, the eLEGS system was later renamed to Esko, and eventually EskoGT. The EskoGT uses push buttons, and force and motion sensors for control, and can has a maximum speed of 3.2 km/hr with 6 hours battery. The suit is a battery-powered lower extremity exoskeleton designed to assist the movement of stroke and spinal injury patients.

The suit is slower than a wheelchair, and its primary operation performs prepared movements, rather than purely aiding movement. While the suit may assist those with "upper extremity motor function of at least 4/5 in at least one arm", the suit is not an improvement on standard human movement and the mechanical design of the suit is "not intended for sports or stair climbing" making its use limited (Charara, 2015)

### 2.1.3 Raytheon XOS Exoskeleton

Raytheon unveiled the Raytheon XOS Exoskeleton in 2008. The XOS like the HULC used force and motion sensors for control and can support 23kg with each arm. It was full body suit capable of mimicking the user's movements. In 2011, six years ago Raytheon declared that the XOS was "now a mere five years away from production", they have since made no public comments regarding the future of the suit(Karlin, 2011)

### 2.1.4 Warrior Web

During DAPRA's 2016 Demo Day they displayed the Warrior Web non-rigid exoskeleton. It used explicitly embedded commands to assist with walking specific ankle motions (DARPA, 2015). The suit has had problems with malfunctions, is unpredictable in uneven terrain, and cannot transfer between running and walking states (Cornwall, 2015).

### 2.1.5 Hybrid Assistive Limb (HAL)

The Hybrid Assistive Limb (HAL) developed by Cyberdine in 1997. The HAL's iterations include a battery-powered lower extremity exoskeleton and a full body exoskeleton.The HAL uses force sensors and bioelectrical impulses to measure muscle contractions to indicate when embedded commands to simulate walking should be triggered.

Despite applying for USA FDA approval in 2014, the HAL is yet to be granted approval in the US (Cyberdyne, 2015).

## 2.2 Design flaws and limitations

As noted by Dunietz (2017) when using an exoskeleton, 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.". Many of these problems can be considered inherent to using force as an input for positional control, or use "jarring" (Cornwall, 2015) preprogramed movements which are "a bit like being a marionette with four wires controlling my legs" (Cornwall, 2015).

Any system which is dependent on preprogramed rigid movements is inherently going to be limited in its finite range of movements. Such systems dependent on embedded commands will remain unintuitive and maladaptive to dynamic conditions and environments.

Force based systems use the application of force by the pilot to indicate the desired position of the suit. However, should the force thresholds for movement be made too insensitive the entire suit may become sluggish, cumbersome, and exhausting to use. Conversely, should the force thresholds for movement be made too sensitive the system may develop jitter, and lags between movement and sensing combined with physical inertia may result in the system moving and applying force the pilot, creating a unstable resonant feedback loop.

Consider the following:

- The pilot at all times will remain inside the suit, so position only needs to measured within the suit;
- If the pilots configuration is assumed to be the desired position of the suit, then the error is difference between the pilots position and the suits position if it were perfectly concentric around the pilot;
- If we measure the position of the pilot relative to the suit, the position of the suit relative to the pilot is known; and,
- 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).

Rather than attempting to derive the designed position of the pilot for their force application to the suit; a control system will be developed that uses the pilot's position to determine the pilot's desired position for the suit.

# 3 Project Plan

## 3.1 Functional Description

As seen in Figure 4, a functional control system must understand and observe the current state and desired state of the suit and pilot. To achieve or approach the desired state, the system must understand what needs to be changed based on the current state of the suit, and the desired state as indicated by the pilot.

As seen in Figure 2, the position of any linear limb of a fixed length can be described by its angular position in relation to a fixed axis. Therefore, by measuring the position of the limb, via proximity, in relation to the joints of the system the overall position of the pilot can be determined. At a point offset from its related joint an array of sensors (ostensibly IR transmitter/receiver arrays) will be used to measure the position of each limb, and therefore the position of the pilot and the configuration space.

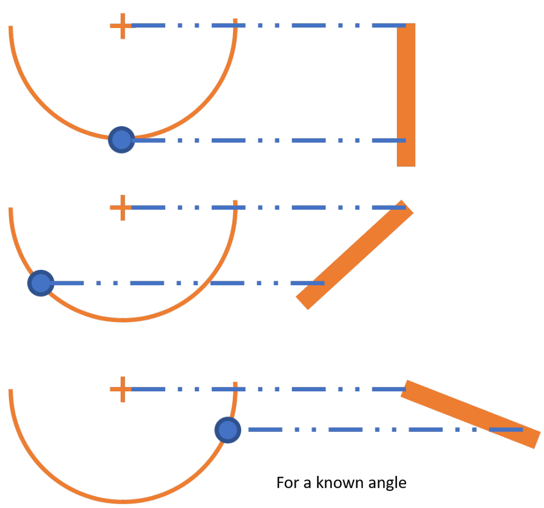



Figure 2: The orientation of a bar of fixed length can be described by its angular position in relation to a fixed rotational axis.

To understand the current state of the suit, the position of the suit and its interactions with the environment must be observed. Determining the position of the suit in relation to itself (e.g. current actuator positions) will be treated as within the scope of the mechanical design exclusively. The orientation of the system, in particular the torso, will be measured via an accelerometer. To observed the interaction of the system with the environment, the force applied to the environment will be measured. Force application will be measured from force sensors and derived from torque sensors. Torque sensors will be treated as within the scope of the mechanical design exclusively. Aside from the torque output of the limbs, the system is concerned with the force output and interactions with the pilot in two contact zones: the feet, and the nates (derriere).

Force output of the system, which for safety will be capped, will be a function of the current force applied in relation to the desired force and the required force. The desired force applied by the pilot is how much force the user wishes to apply to a given surface (e.g. the force applied by a gentle footfall vs. a stomp). The required force is the amount of force required to maintain a position (e.g. the force applied to the ground by standing). An internal force sensor will be used to measure the desired force of the pilot at each of the contacts points. External force sensors, which mirror the internal sensors will be used to measure the force output of the system.

As seen in Figure 3, mirrored sensors are to differentiate between the user placing a contact point (e.g. their feet) on or near a surface compared to placing their weight on a contact surface. Until force is applied to the internal force sensor the suit will behave as it does in any other circumstance: however; once force is applied to the internal sensor the system will apply the minimum additional required force to maintain the users desired position. Through this a suit which never applied more than 5N of force in normal operation can provide the necessary normal force to support the weight of a standing pilot.

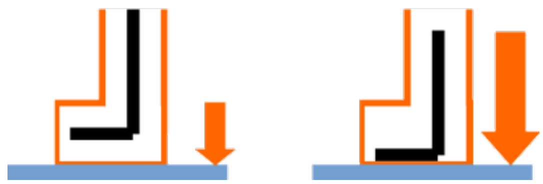


Figure 3: The suit will apply a very low maximum force under normal conditions. Force applied internally (e.g. standing) indicates to increase the force output

If the state of the current state the suit and desired state of the pilot can be observed, then the desire position of the suit can be derived. CONTROLS, I am so fucked

### 3.1.1 Objective and Core tasks

The core tasks of the project are to:

- Create sensor arrays to measure the position of the pilot;
- Measure the force applied to the environment in the contact zones;
- Measure the orientation of the suit for kinematic purposes; and,
- Developed controls theory and software to create the desired system behaviour.

Each of these core tasks build to the objective of the project: *to engineer and construct a proof of concept for a novel exoskeleton proximity based control system.*

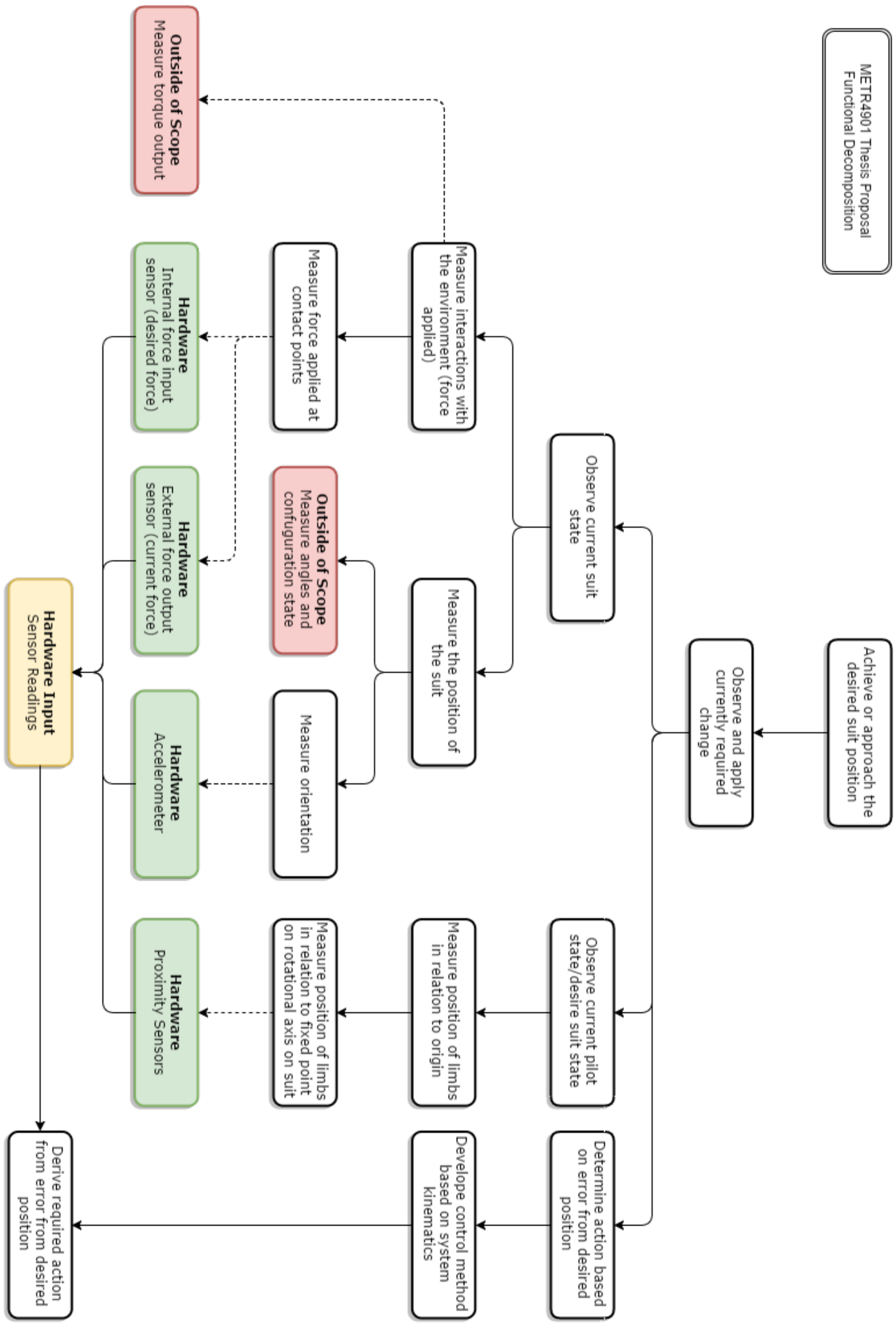
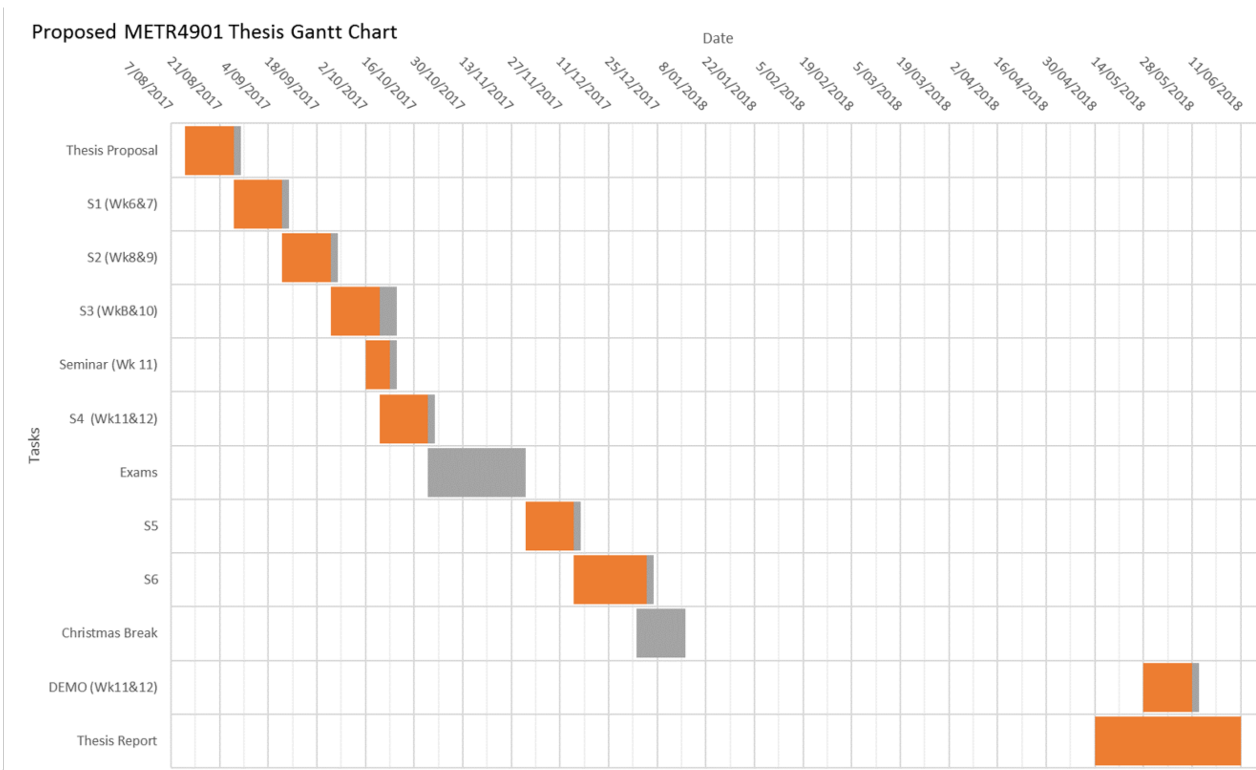



Figure 4: Functional Decomposition

## 3.2 Timeline and Milestones

### 3.2.1 Milestones and Deliverables

As shown in Figure 5 (larger version available in 6), the project will be subdivided into fortnightly iterations on the design. Each iteration will be half engineering and design phase,and half building and commissioning phase. This will ensure that implementation and material progress remains a priority, while guaranteeing every stage is engineered in the context of build and the greater solution, avoiding speculative design. Explanations of the iterations, their deliverables, and completion criteria can be found in Table 2: Stage Breakdown.




| | Thesis Proposal | S1 (Wk6&7) | S2 (Wk8&9) | S3 (WkB&10) | Seminar (Wk 11) | S4 (Wk11&12) | Exams | S5 | S6 | Christmas Break | DEMO (Wk11&12) | Thesis Report |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Start | 11-Aug | 25-Aug | 8-Sep | 22-Sep | 2-Oct | 6-Oct | 20-Oct | 17-Nov | 1-Dec | 19-Dec | 14-May | 30-Apr |
| Duration (Days) | 14 | 14 | 14 | 14 | 7 | 14 | | 14 | 21 | 0 | 14 | 42 |
| Slack (Days) | 2 | 2 | 2 | 5 | 2 | 2 | 28 | 2 | 2 | 14 | 2 | |
| End | 25-Aug | 8-Sep | 22-Sep | 6-Oct | 9-Oct | 20-Oct | 20-Oct | 1-Dec | 22-Dec | 19-Dec | 28-May | 11-Jun |

Date

Figure 5: Proposed Gantt Chart

Planning into the new year would be entirely speculative: however, activities will focus on the implementation and optimisation of the system's control. While not stated in Table 2: Stage Breakdown further research and investigation, especially into control theory, will be conducted throughout the entire project. Also at various points within the project a design review will be conducted with the thesis supervisor, ostensibly every second stage. Periods of slack, e.g. after exams, during the Christmas break, will also be harnessed to progress the project and ensure the milestones are met.

Table 2: Stage Breakdown

| **Stage** | **Task** |
|---|---|
| Stage 1 (Wk6&7) | **Deliverable:** Prototype of IR proximity sensor array<br>**Purpose:** Early progress and testing of the proximity sensors will aid in further design iterations and forecast possible engineering challenges, integral to core task of creating a sensor arrays to measure the position of the pilot<br>**Criteria:** Readings from an array of minimum four IR sensors are able to concurrently read and proximity is correct to 10 mm |
| Stage 2 (Wk8&9) | **Deliverable:** Prototype of contact force sensor<br>**Purpose:** Early progress and testing of the proximity sensors will aid in further design iterations and forecast possible engineering challenges, integral to core task of measuring the force applied to the environment<br>**Criteria:** Reading from an array of minimum two force sensors are able to concurrently read and weight is correct to 1 kg. |
| Stage 3 (WkB&10) | **Deliverable:** *Final* mechanical build for proximity sensors and force sensors<br>**Purpose:** Finalise mechanical build to begin integration with mechanical portion of project, create presentable materials for thesis seminar (Wk11) to better demonstrate progress<br>**Criteria:** Criteria: Feedback on the quality of the physical build and design sought from thesis advisor and seminar assessors |
| Stage 4 (Wk11&12) | **Deliverable:** Prototype of integration with mechanical suit, integration of accelerometer, incorporation of feedback<br>**Purpose:** To commission sensor portion of project, integral to core task of measuring the orientation of the suit for kinematic purposes<br>**Criteria:** Reading from accelerometer is correct to 30 degrees. Specifics of integration timeline will be dependent on coordination between the sides of the project. |
| Exam | During exam block and week 13 of semester minimal significant progress is expect. Work will continue, but deliverables are unlikely to be produced. |
| Stage 5 | **Deliverable:** *Final* build for integration with mechanical side, including communications<br>**Purpose:** To finalise sensor portion of project<br>**Criteria:** Sensors are able to perform at full functionality when mounted to the mechanical suit |
| Stage 6 | **Deliverable:** Begin controls portion of project, integrate controls with off board processor<br>**Purpose:** Integral to core task of developing the controls theory and software to create the desired system behaviour, control of the system may be simplified by using dedicate software environments or off board processors<br>**Criteria:** Embedded communication software able to communicate (2 way) with off board processor. |
| Christmas Break | During the immediate Christmas break minimal significant progress is expect. Work will continue, but deliverables are unlikely to be produced. |

### 3.2.2 Integration

As the project has been subdivided into mechanical and electrical design integration will need to occur. While communication throughout the project will be ongoing, Stage 4 (Weeks 11 and 12) of the project will be dedicated to integration of the project. During this period of time three tasks must be completed:

- Integration of pre-established communications protocols;
- Physically mounting of the sensors to the suit; and,
- Testing and verification of the full suit.

To ensure integration is without setbacks, in the design phase certain agreements will be reached and standards will be set. There will be a standard communications protocol that will allow the motor drivers and motor microcontrollers to communicate with the sensors and sensor microcontrollers, while the sensor microcontrollers also maintain the capability to communicate with offboard processors. The physical design will be discussed between the two sides of the project and mounting places and methods for the sensors will be pre-arranged before the physical construction of both the sensors and suit. Dimensions of the suits, and positions of sensors will be detailed as early as possible to aid with the controls of the system.

## 3.3 Constraints, Dependencies, and Requirements

The scope of the project is most severely constrained the thesis duration, which translates into the mechanical design being constrained and simplified. The electrical and controls portion of the project are mostly exempt from to constraints, excluding occupational health and safety rules.

To hasten the physical construction, as the goal of the project is working controls not novel electrical design, many prefabricated electrical components may be used in the project. The project will be dependent on the efficacy and reliability of these components. The project will also use various software libraries, while some guarantees may exist for their reliability, the project will be dependent on their operation.

Within the project however, the two sides of the project will be very dependent on each other. While to ensure that all work is completed individually the sides may progress to produces individual partial prototypes, to create a full proof of concept the sides will need to integrate with each other. As a result, both sides of the project are dependent on each other conforming to the same mutually set standards and protocols for communication, mounting, and positioning.

The design will attempt to meet all the requirements for movement set in Table 1: Required Movements without malfunctioning during demonstration. In addition, the build quality of the design must be aesthetically pleasing.

# 4 Risk Assessment

Risks to the thesis project will be classified using table 3.

| | | Impact | | |
|---|---|---|---|---|
| | | Low | Medium | High |
| Likelihood | Low | LOW | LOW | MEDIUM |
| | Medium | LOW | MEDIUM | HIGH |
| | High | MEDIUM | HIGH | HIGH |

Table 3: Risk Assessment Table

## 4.1 Project Risks

A risk assessment of the risks that threaten the thesis, but not the occupational health and safety (OH&S), was conducted and may be found in Table: 4.

## 4.2 Occupational Health and Safety Risks

A risk assessment of the risks that threaten occupational health and safety (OH&S) related to thesis was conducted and may be found in Table: 5, note that this risk assessment is project specific and in addition to safe lab practices.

Table 4: Project Risk Assessment

| Risk | | Without Mitigation | | | Mitigation | With Mitigation | | |
|---|---|---|---|---|---|---|---|---|
| Description | Likelihood (L/M/H) | Outcome | Impact (L/M/H) | Risk Factor | Strategy | Outcome | Impact (L/M/H) | Risk Factor |
| Supervisor unavailable for substantial period of time | L | Assistance or guidance required may be unavailable | M | L | Methods of remote communication will be established (e.g. email) | Urgent communication may be conducted. | L | L |
| Supervisor falls ill and/or is away for significant amount of time | L | Will not be able to meet in person to discuss issues with the project | M | L | Keep in contact via email or phone | Discussions will be carried out over email | L | L |
| Data loss | M | Previous progress may be lost | H | H | A cloud hosted git repository shall be used. Local backups of files | In the event of data loss or a mistake previous versions of the project may be recovered. | L | L |
| Laptop (primary tool) damaged | L | Previous progress, software suites, and configurations may be lost | H | M | Caution will be exercised to preserve laptop. | Likelihood of risk is reduced. | H | |
| Illness or personal matter slows progress | M | Progress may be delayed. Deadlines may need to be postponed | H | H | Avoid activities that increase the risk of illness. Adopt strategies outlined in "Project is delayed" | Likelihood of risk is reduced. See "Project is delayed" | M | M |
| Project is delayed | L | Sacrifices in university work, external works, and personal life may be required | H | M | Weekly public meetings with supervisor ensure accountability. Fortnightly deadlines have been set, as seen in 3.2: Timeline and Milestones, so setbacks and delays can be identified and corrected. | Project is broken into increments of progress, preventing a backlog. | M | L |
| Delivery of required component delayed | H | Progress may be delayed. Deadlines may need to be postponed | H | H | Identify and order physical components as early as possible to provide a buffer of time. | Even if parts are delayed, a delay in project progress may be avoided | L | M |

Table 5: Occupational Health and Safety Risk Assessment

| Risk | | Without Mitigation | | | Mitigation | With Mitigation | | |
|---|---|---|---|---|---|---|---|---|
| Description | Likelihood (L/M/H) | Outcome | Impact (L/M/H) | Risk Factor | Strategy | Outcome | Impact (L/M/H) | Risk Factor |
| Running power from computer | M | Electric shock | M | M | Follow UQ standards for electrical safety. See supervision, advice, and sign off from supervisor. Never perform potentially hazardous operations alone. | Reduced risk of electrocution and electric shock. Medical attention may be available as needed | L | L |
| Running power from mains power | M | Electric shock, electrocution | H | H | Follow UQ standards for electrical safety. See supervision, advice, and sign off from supervisor and an electrician. Never perform potentially hazardous operations alone. | Reduced risk of electrocution and electric shock. Medical attention may be available as needed | H | H |
| Joint Pinching at exoskeleton actuation points | M | Bodily harm to pilot, if flesh is pinched | H | H | Suit should be designed to prevent pinch points. Pinch points should be covered. Pinch points should be physically distant from pilot. | Threat may be avoided | L | M |
| Hyperextensionat exoskeleton actuation points | M | Bodily harm to pilot, if joints are over extended | H | H | Physical mechanical limiters should be integrated into the system to prevent prohibited movements | Threat may be avoided | L | L |
| Bludgeoning by suit | H | Bodily harm to pilot, if stuck by suit | H | H | Motors and power should be selected to minimise power output. Torque output should be limited. | Uncontrolled movement no longer threatens bodily harm | L | M |
| Crushed by suit | M | Bodily harm to pilot, if crushed by falling suit | H | H | Suit should never be freestanding but instead held in place by mounts | Threat may be avoided | L | L |

# 5 References

Charara, S. (2015, July 9). This robotic exoskeleton helps paralysed patients to walk and it's getting smarter.Retrieved August 23, 2017, from wareable.com: https://www.wareable.com/saves-the-day/exoskeleton-paralysed-patients-ekso-bionics-gt-sarah-thomas

Cornwall, W. (2015, October 15). /news/2015/10/feature-can-we-build-iron-man-suit-gives-soldiers-robotic-boost. Retrieved August 20, 2017, from sciencemag.org: http://www.sciencemag.org/news/2015/10/feature-can-we-build-iron-man-suit-gives-soldiers-robotic-boost

Cyberdyne. (2015, August 1). CYBERDYNE Inc. has begun seeking approval from the U. S. Food and Drug Administration (FDA). Retrieved August 23, 2017, from cyberdyne.jp: https://www.cyberdyne.jp/english/company/PressReleases_detail.html?id=1075

Cyberdyne. (2016). What's HAL. Retrieved August 19 2017, from cyberdyne.jp: https://www.cyberdyne.jp/english/products/HAL/

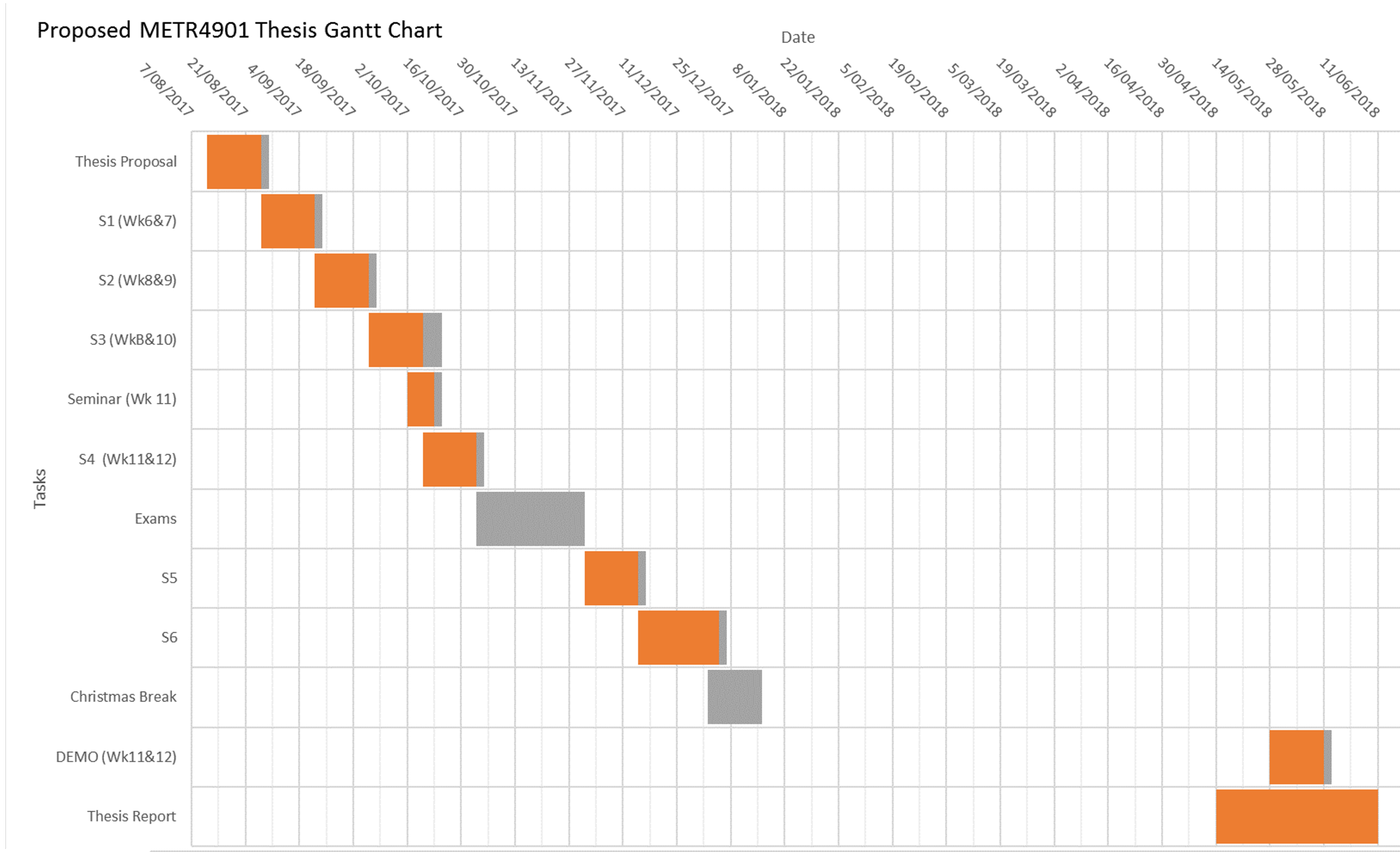
DARPA. (2015). Warrior Web. Retrieved August 24, 2017, from darpa.mil: https://www.darpa.mil/program/warrior-web

Dunietz, J. (2017, July 27). Robotic Exoskeleton Adapts While It's Worn. Retrieved August 20, 2017, from scientificamerican.com: https://www.scientificamerican.com/article/robotic-exoskeleton-ldquo-evolves-rdquo-while-its-worn/

Exoskeleton Report LLC. (2017, August 24). What is an exoskeleton? Retrieved from http://exoskeletonreport.com: http://exoskeletonreport.com/what-is-an-exoskeleton/

Karlin, S. (2011, July 29). Raytheon Sarcos's Exoskeleton Nears Production. Retrieved August 11, 2017, from spectrum.ieee.org: http://spectrum.ieee.org/at-work/innovation/raytheon-sarcoss-exoskeleton-nears-production

# 6 Appendix: Gantt Chart




| | Thesis Proposal | S1 (Wk6&7) | S2 (Wk8&9) | S3 (WkB&10) | Seminar (Wk 11) | S4 (Wk11&12) | Exams | S5 | S6 | Christmas Break | DEMO (Wk11&12) | Thesis Report |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Start | 11-Aug | 25-Aug | 8-Sep | 22-Sep | 2-Oct | 6-Oct | 20-Oct | 17-Nov | 1-Dec | 19-Dec | 14-May | 30-Apr |
| Duration (Days) | 14 | 14 | 14 | 14 | 7 | 14 | | 14 | 21 | 0 | 14 | 42 |
| Slack (Days) | 2 | 2 | 2 | 5 | 2 | 2 | 28 | 2 | 2 | 14 | 2 | |
| End | 25-Aug | 8-Sep | 22-Sep | 6-Oct | 9-Oct | 20-Oct | 20-Oct | 1-Dec | 22-Dec | 19-Dec | 28-May | 11-Jun |

Date

Figure 6: Proposed Gantt Chart