1 Title page

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THESIS SUBMISSION

DR PAUL POUNDS

2 Abstract

200-300 words written last

3 Executive summary

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1 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 kt. Force based methods encounter stability problems and may increase the exertion required to complete a task kt.

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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Part One: Preamble

2 Background and Problem breakdown

2.1 Existing Technologies and limitations

Exoskeleton technology began in 1890 kt, with Nicholas Yagin, with the development of a passive device that used compressed gas to assist in human movement. However, it was not until the 1960s that the first attempt at a practical power exoskeleton was developed. The Hardiman kt, 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.

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.

2.1.1 HULC kt

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. 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" kt and has been succeeded by the TALOS project kt.

2.1.2 EskoGT kt

In 2010 the original developer of the HULC, Esko Bionics revealed the Exoskeleton Lower Extremity Gait System (eLEGS). With a maximum battery life of 6 hours and maximum gait of 3.2m/s kt, 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", the suit is slower than a wheelchair and is not an improvement on standard human movement

2.1.3 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 kt. 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.

2.1.4 Warrior Web

The Warrior Web non-rigid exoskeleton was first demonstrated at the 2016 DARPA Demo Day. 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. kt (Cornwall, 2015).

2.1.5 Hybrid Assistive Limb (HAL)

In 1997 Cyberdine unveiled the Hybrid Assistive Limb (HAL). The HAL's iterations include a battery-powered lower extremity exoskeleton and a full body exoskeleton. 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 kt

2.2 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 (2017) kt 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." 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) kt and inadequate.

2.3 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.

2.4 Proximity as a solution

Consider the following:

a) For controlling the suit, it may be assumed that the user is inside the suit during operation;
b) The users desired position for the suit may be treated as their personally bodily position;
c) 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;
d) 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,
e) 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:

a) In a circumstance where the exoskeleton encounters an obstacle it is desirable to regulate and control the force output of the system;
b) It is desirable to decouple the control of force output and speed (a noted flaw with force-based control methods);
c) 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,

d) 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:

a) 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;
b) Under these circumstances the constant offset between the user and the system will not be maintained;
c) The user then may make contact with the internals of the suit;
d) 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;
e) 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;
f) 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,
g) 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.

2.4.1 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.

2.4.2 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.

2.4.3 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.

2.4.4 Stability and Safety

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2.5 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 of the requirements of each level of functionality. These are outlined as follows.

2.5.1 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.

2.5.2 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.

2.5.3 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.

2.5.4 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.

2.5.5 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.

2.5.6 Information Required

As seen in kt, there are four main pieces of information required to control the system at all levels.

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	✓	✓	✓	✓

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.

3 Scope

3.1 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 kt, to create a proof of concept for the system only a lower extremity exoskeleton is required.

3.1.1 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.

3.1.2 Required Systems

A full functional decomposition can be found in kt.

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

3.1.3 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.

3.1.4 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.

3.2 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:

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

3.2.1 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.

Part Two: Design

4 Functional Decomposition

The system defined by the scope, see kt, was decomposed into its major function requirements. Functional decompositions were then completed for the major subsystems in their respective sections (see kt, kt, kt, kt, and kt). This section outlines that major function requirements of the system.

5 Subsystem One: Relative Position of Pilot

5.1 Requirements

5.2 Possible solutions

5.3 Justification of chosen solution

5.4 Components list of chosen solution

5.5 Performance

6 Subsystem Two: Force applied by and to Exoskeleton

6.1 Requirements

6.2 Possible solutions

6.3 Justification of chosen solution

6.4 Components list of chosen solution

6.5 Performance

7 Subsystem Three: Controls and Decision Making

7.1 Requirements

7.2 Possible solutions

7.3 Justification of chosen solution

7.4 Components list of chosen solution

7.5 Performance

8 Subsystem Four: Communications

8.1 Requirements

8.2 Possible solutions

8.3 Justification of chosen solution

8.4 Components list of chosen solution

8.5 Performance

9 Subsystem Five: Actuation Systems

9.1 Requirements

9.2 Possible solutions

9.3 Justification of chosen solution

9.4 Components list of chosen solution

9.5 Performance

Part Three: Outcomes

10 Holistic integration of requirements

11 Demo

12 Recommendations and further research

13 Conclusion

14 References

15 Appendices

15.1 Code

- Firmware in C
- Matlab

15.2 PCBs

15.3 CAD drawings