The industrial pneumatic walking platform

The design, build and coding process of a walking machine

By

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Author’s declaration

I declare that this thesis is my own account of my research and contains as its main content work which has not previously been submitted for a degree at any tertiary education institution.

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[Author]
Abstract

The main aim of the thesis is to study and replicate quadruped movement in the hopes of utilizing its biological behaviour to integrate in machinery and aid work undertaken in industrial environments. The thesis focuses on the design, build and programming of a quadruped walking platform for the main purpose of showcasing, industrial grade carrying purposes as well as a potential teaching tool. Inspired by the biological movements of quadruped animals, the machine must be able to efficiently move from one point to another with sufficient reactive control, while simultaneously carrying significant weight. The control of the overall machine will be done through a microcontroller, actuating different parts of the machine while sensing its current states.

The challenges faced during this thesis centred on the mimicking of biological behaviour and motion: Quadrupeds move around using a combination of synchronised leg movements and environmental sensory feedback. Replicating this behaviour proved to be difficult, even at a simpler scale.

Ideally the project must be able to accommodate the continuation of work by future students, by providing any additional appropriate documents.
Acknowledgements

Prima facie, I would like to sincerely thank the academics that helped and advised me through my thesis project, notably Graeme Cole, associate professor and lecturer, for supervising and aiding me through the many processes and challenges.

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Contents

I. Introduction .................................................................................................................... 8

II. Background .................................................................................................................. 9

III. Leg and joint movement ............................................................................................. 11
   1. Design ...................................................................................................................... 12
      a. Initial Ideas/research ........................................................................................... 12
      b. The initial strap design ....................................................................................... 13
      c. The rack and pinion row design ......................................................................... 14
      d. The strap and hinge concept ............................................................................... 15
      e. Final leg design .................................................................................................... 16
   2. Build ......................................................................................................................... 17
   3. Programming .......................................................................................................... 20
   4. Results ...................................................................................................................... 21

IV. Frame/chassis and housing ......................................................................................... 22
   1. Design ...................................................................................................................... 22
   2. Build ......................................................................................................................... 29
   3. Results ...................................................................................................................... 29

V. Feet ............................................................................................................................... 31
   1. Design ...................................................................................................................... 31
      a. The ball foot design ............................................................................................ 32
      b. Free-moving flat foot design (with iterations) .................................................... 34
   2. Build ......................................................................................................................... 38
   3. Programming/testing ............................................................................................. 39
   4. Results ...................................................................................................................... 40

VI. Control hardware: Pneumatic and electrical setup ...................................................... 42
   1. Airflow setup ........................................................................................................... 42
   2. Electrical setup ...................................................................................................... 46
   3. Results ...................................................................................................................... 47

VII. Overall build .............................................................................................................. 51
   1. Programming ........................................................................................................... 51
   2. Testing ...................................................................................................................... 52
   3. Results/issues ........................................................................................................ 53
      Stability issues ....................................................................................................... 54

VIII. Future work/unfinished work .................................................................................. 58
1. Sensors .................................................................................................................. 58
2. “Intelligent” walking.............................................................................................. 60
3. Added stability........................................................................................................ 61
4. Wireless communication....................................................................................... 61
   Safety checks .......................................................................................................... 61
IX. Conclusion ............................................................................................................ 62
X. Appendix/Additional information......................................................................... 63
  1. Force to width relation in regards to pressure....................................................... 63
  2. Valve types and functions ................................................................................... 64
  3. 68HC912 microcontroller ................................................................................... 67
  4. Fatigue test ........................................................................................................... 67
  5. Hooke’s law, spring coefficient .......................................................................... 68
  6. Animal gait (canine) ............................................................................................ 69
  7. Final dimensions ................................................................................................ 70
     Calculated weight of chassis ............................................................................... 70
  8. Calculated carrying capacity .............................................................................. 71
Works Cited .............................................................................................................. 72
List of figures

Figure 1: Robot-dog by Shiqi Peng (Peng 2006) ................................................................................. 10
Figure 2: Big-Dog by Boston Dynamics (M. Raibert 2008) ................................................................. 10
Figure 3: horizontal to vertical movement ....................................................................................... 14
Figure 4: rack and pinion row design .............................................................................................. 15
Figure 5: strap and hinge design ...................................................................................................... 16
Figure 6: full 1 side design ............................................................................................................... 17
Figure 7: piston to piston build ......................................................................................................... 18
Figure 8: piston to piston build replicated ........................................................................................ 19
Figure 9: one side full build test ..................................................................................................... 19
Figure 10: hinge positions on test build ............................................................................................ 25
Figure 11: hinge distances ............................................................................................................... 25
Figure 12: considered chassis designs .............................................................................................. 26
Figure 13: final chassis design .......................................................................................................... 27
Figure 14: final chassis design top view with hinge positions ........................................................... 27
Figure 15: welding point for stronger bond ...................................................................................... 29
Figure 16: different angles of legs .................................................................................................... 32
Figure 17: ball foot design ............................................................................................................... 33
Figure 18: free-moving flat foot design ............................................................................................ 35
Figure 19: flat foot design iterations ................................................................................................ 35
Figure 20: final foot design .............................................................................................................. 37
Figure 21: final foot design, reiterated .............................................................................................. 39
Figure 22: final foot design, 2nd reiteration ....................................................................................... 41
Figure 23: Naming convention for pneumatic pistons ..................................................................... 43
Figure 24: chassis leg positions and names ...................................................................................... 43
Figure 25: even air distribution during final tests .............................................................................. 44
Figure 26: uneven air distribution during initial tests ........................................................................ 44
Figure 27: pneumatic pistons pressure considerations .................................................................... 46
Figure 28: control setup, pneumatic and electrical ......................................................................... 49
Figure 29: Visual diagram of pneumatic and electrical setup .......................................................... 50
Figure 30: balancing issues representation ...................................................................................... 54
Figure 32: 4/2 valve example, contraction ......................................................................................... 65
Figure 31: 4/2 valve example, extension ............................................................................................ 65
Figure 33: 5/3 valve characteristic diagram ....................................................................................... 65
Figure 34: canine walking motion (4) ............................................................................................... 69
I. Introduction

Around the world, a number of engineering teams have experimented with the replication of animalistic behavior and movement in machines, with different levels of success and aim. The approach taken for this project was of relative simplicity: the machine was to be able to move effectively with few degrees of movement for each leg, allowing limited control but also limited errors to potentially occur. The general focus of the project is to create a machine that would demonstrate the engineering work done at Murdoch University, effectively a showcase project, which must be visually interesting and impressive. What defines this project among others would be its robustness and simple movements to allow more brute motion. This design choice was also done due to time constraints and limited resources.

The main design challenge of this project is to design, build and program an air powered walking platform controlled by a microcontroller which would effectively mimic a biological quadruped’s walking motion through sensory feedback for the purpose of stabilization. The machine would have 4 limbs as a means of locomotion. The main control of the system would be done through an on-board microcontroller, the Motorola 68HC12 (Motorola 2000), providing the required input and output control for the necessary tasks.

The entirety of the project was broken down into three major phases: the designing, building and programming phase. These phases were involved in the process of each part of the machine. Ultimately a great majority of what was planned was achieved. Throughout the thesis the work and research was done closely with John Boulton, an engineering technician at Murdoch University.
II. Background

As the premise of the project is very broad, the first few weeks of the semester mainly involved preplanning and various meetings with the project supervisor, as this is a newly started project and needs clear guidance and planning not only in the short term (semester 2 2016) but also for the longevity of the project. After extensive discussions, brainstorming and research into other similar projects the design and objective of the project was more refined: building and programming a four legged industrial grade walking machine capable of basic environmental detection and basic reactivity, utilizing sensory feedback; “industrial grade” emphasises on the rigidness, brawn and stability of the product/project.

Similar projects that were looked into for development ideas and improvements include:

- The Robo-dog by Shiqi Peng (Peng 2006): the robo-dog (Figure 1) is a project run by a former Murdoch University postgraduate student which involved the design, build and programming of a sensory dependant walking metal dog. The project was a continuous effort done by different students through the years, including Shiqi Peng (Peng 2006), Ashley Cocker (Cocker 2013) and Harold Ear (very recent work, no referencing available) The robo-dog is comprised of a total of 16 small pneumatic pistons and is capable of self-balancing through the use of tilt sensors, as well as ground detection using limit switches on the feet. The machine was intended to walk by imitating an animalistic gait, the walking locomotion of a quadruped animal. Additionally, the movement
of each limb is tracked through the use of potentiometers, allowing the microcontroller to reliably react to the movements of the dog. Recent additions include a wireless communication capability as well as more accurate ground detection. The robo-dog has come a long way and is currently capable of walking through sensory feedback, although it is still an ongoing project for current and future students.

- Boston Dynamics' various projects (M. Raibert 2008). Boston Dynamics is an American design company focused on engineering and robotics. They are most famously known for the design and development of quadruped robots, including BigDog (Figure 2), a military-grade focused self-balancing walking machine. The quadruped machine uses gyroscopic sensory feedback in order to balance itself and is equipped with four equal legs, allowing it to move on uneven surfaces better than wheels can. The project at hand was greatly inspired by BigDog’s design and concepts, as well as other similar projects worked by Boston Dynamics such as LS3 (Dynamics 2016).
HyQ, the hydraulic quadruped by Italian institute of technology. HyQ was started by a man called Claudio Semini as a PhD project at the Italian Institute of Technology (IIT). The intended aim of HyQ was to design and build a quadruped robot with enough versatility to move through different animalistic patterns such as walking and running, and jumping on both smooth and rough terrain. The machine is able to walk autonomously using a series of sensors and various actuating pivot points, which can effectively recreate basic proprioception (Miller 2010). HyQ is still an ongoing project at IIT.

As previously stated, the approach to the design and build of the machine was developed on a part-by-part basis. This included the leg and joint movement, the body/chassis and housing, the feet, and the pneumatic and electrical setup. The following is the work done for each part of the machine, discussing the different aspects and challenges for each part in its design, build and programming where it applies.

### III. Leg and joint movement

The legs are the main focus of the machine, allowing proper and efficient locomotion of the body if designed, built and programmed correctly. The following details the different steps taken in the realization of the legs for the project. The university has a stock of pneumatic pistons of varying lengths and widths which are available for the project at hand.
1. Design

There are various ways to create locomotion though to keep a sense of relative simplicity in both building and programming the legs consist of two pistons per leg and four legs in total. Three piston types are available for the project, which will be referred to as pneumatic pistons A, B and C. Each piston type has different specifications:

- Pneumatic piston A is 34cm in length and 5.8cm in width, six of this type were available
- Pneumatic piston B is 34cm in length and 7.4cm in width, three of this type were available
- Pneumatic piston C is 28cm in length and 7.4cm in width, three of this type were available

In order to keep a level of stability and balance, ideally the legs should be as similar as possible, though the project requires 8 pistons. Therefore, keeping the lengths consistent, 6 pistons of type A were chosen and 2 pistons of type B. Type C pistons were not used due to their shorter length.

Now that the pistons were chosen, the next task was to put them together in a way that could create a motion of walking in a constant continuous loop.

a. Initial Ideas/research

In order to create a proper walking motion a basis of animalistic movement was taken in consideration as inspiration, following the premise of a horizontal motion and a vertical motion working together at a fairly simplistic level. There
are a number of different ways to create a walking motion with two pistons. Research into possible designs was done, following the idea of one piston used for horizontal motion and one piston for vertical motion, similarly to a walking canine (see appendix, page 68). Keeping in mind the motion of lifting a leg (vertical motion), moving it forward (horizontal motion) and then setting it down (vertical motion) in a fluid and systematic motion, a few design ideas and concepts were considered for viability.

b. The initial strap design

The first design considered utilized a strap which would connect two pneumatic pistons perpendicularly, creating an alternating movement of horizontal extension/contraction using one piston of type A, and vertical extension/contraction using another pneumatic piston of type B (Figure 3). The concept seemed like a good idea, but upon further research and consultation it was found that the concept was not viable because of the uneven force distributed throughout the leg, certain parts of the leg would be subjected to immense stress from the carry weight and the weight of the machine itself, notably the horizontal extension and strap connecting both pneumatic pistons would be susceptible to failure. The significant localized force would make the joint connection very prone to breaking. Additionally pneumatic piston A is also subjected to a great amount of stress in the connection to the body frame, which can easily break as well. This design had a high likelihood of failure due to its weak connecting points, and therefore was not chosen.
After extensive consideration of the first design, it was decided that a simple horizontal/vertical movement was highly unfavorable, and so a new movement design was considered. The new design involved a horizontal pivot coupled with a vertical extension/contraction, similarly to walking on stilts, or even similarly to a rowing motion. Therefore with a new motion concept in mind, another design considered utilized a rack and pinion: The linear motion from pneumatic piston A, equipped with a rack, is translated into a rotational motion onto pneumatic piston B using a pinion, or a cog, allowing pivoting of pneumatic piston B (Figure 4). This concept was favorable and no issues stood out both in short term and long term. The issue came when consulting about the parts necessary for the build of the leg, notably the rack and pinion being fairly expensive and hard to source. For these reasons the design was unfavorable.
d. The strap and hinge concept

A third design was thought of, utilizing similar traits from the previous two design ideas, notably the strap concept as well as the pivot concept. Pneumatic piston A connects to pneumatic piston B in a similar manner as the first design concept, though at a higher point on the piston’s chamber. Piston B is then set on the same pivot point as in the rack and pinion concept (Figure 5), utilizing the already-present hinge available on the pneumatic pistons. These two designs ideas provide the desired tilting motion (Figure 5). An extra design consideration must be addressed: pneumatic piston A will slightly tilt every time it extends in order to accommodate the arc movement of pneumatic piston B. In order to resolve this issue piston A will also be connected through its already-present pivot point in order to allow relatively free movement (Figure 5, circled), rather than keeping it stationary onto the machine frame. The latter design was therefore chosen for the final build, providing proper movement control while being feasible both in terms of a physics perspective and cost/parts perspective. It should be noted that an additional consideration must be made in the

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**Figure 4: rack and pinion row design**
connection between the two pistons, as the angle between the two will not remain constant during movement.

![Diagram](image)

Figure 5: strap and hinge design

e. Final leg design

Each new leg design was analyzed in the order described above. The final leg design was a continuous iteration and combination of design ideas. With the final leg design chosen, it was important to find the right pneumatic pistons for the appropriate jobs. It was said earlier that pneumatic pistons A and B were chosen for the build, and that there are 6 pneumatic pistons of type A and 3 pneumatic pistons of type B. Pneumatic pistons A will be used for the horizontal movement, as well as two more for the front legs of the machine, whereas 2 pneumatic pistons B will be used for the vertical movement of the back two legs of the machine, to capture a more animalistic build with both hind legs being relatively bigger and stronger (greater width = greater force, more on this in “additional information” section). Note that this decision has no impact on
efficiency of movement, the machine should move equally well forward and backward. Figure 6 shows the side view of the leg mechanism, with pneumatic piston B representing the back of the machine. For a future reference, in order to clearly discuss the design of the legs, the vertical pneumatic piston will be referred to as a pneumatic piston A, and the horizontal pneumatic piston will be referred to as a pneumatic piston B.

![Diagram of leg mechanism with labeled parts A and B](image)

**Figure 6: full 1 side design**

2. **Build**

The entirety of the legs has been designed. The next step involved the building and testing of the design concept in order to make sure no issues have been overlooked.

When starting the building process a rudimentary build was done, though unsuccessfully due to the build needing to be sufficiently durable for a project intended to withstand high forces. The minor aspects such as the connection between the two pneumatic pistons and the pivot design were therefore handed
to John Boulton (Boulton 2016) to figure out, as he has greater knowledge in the design of these types of builds, having had built similar designs in the past. John Boulton attempted a few builds while keeping in mind the main design of the leg, and came out with a sturdy solution for both the connection between the two pneumatic pistons as well as the pivot points. The connection between the two pneumatic pistons was made using a metal bracket and a rose joint as seen in Figure 7 which allowed angular change between the bracket and pneumatic piston A, as there was a change in the angle between pneumatic pistons A and B when A extended. To allow pivoting for both pneumatic pistons the pre-made pivot points for both pneumatic pistons were used (Figure 6), by inserting a long bolt to allow free angular movement.

Once the leg was fully built, it was mounted onto a temporary wooden frame for quick testing purposes. The leg was then tested for movements and strain levels (movements with load, unnatural movements, etc.) in order to test the durability and viability of the design, lifting, extending and contracting at high loads continuously to allow any errors to occur, though none occurred after
rigorous testing. The leg design was therefore approved and replicated using more common parts (Figure 8).

With the successfully built second leg mounted onto the temporary frame, half of the entirety of the locomotion limbs were built and ready to be tested and programmed in conjunction. Figure 9 shows the two built legs mounted onto the test bench, with the commissioned leg build on the left and the replicated leg setup on the right.
3. Programming

After having built two out of four of the required legs for the full machine build, the legs were tested for efficiency and proof of concept. The initial tests were done on one leg, using two 5/2 way direction solenoid valves (Festo 2002), allowing cylinder extension and contraction through basic relay control. Using basic digital output controls from the 68HC912 microcontroller (Motorola 2000) and two 5/2 valves, one for each pneumatic piston, initial tests were successfully run on one of the legs allowing proper arc movement and foot extension to the ground. To further test rigidity and fluid motion, the leg was lowered to lift the test bench solely using the extension piston, pneumatic piston B. This test was done in part to verify the movement capabilities of a single leg under load, as well as a form of fatigue test (R. 1949) for the different connecting parts of the leg. Note that a fatigue test is done until failure of the tested device, though due to time constraints this was avoided. The fatigue test involved a continuous repetitive lift and drop cycle of the test bench, weighing approximately 25 kg, for approximately 2 hours. The result was again a success, with the leg providing ample movement and showed little to no weakness under load. After rigorous repetitive testing no issues arose.

The next step of testing involved the two legs for simultaneous control, as well as a replacement of the valves from 5/2 way directional valves (Festo 2002) to 5/3 way directional valves (Festo 2002), adding more control and complexity to the test bench. The initial test involved two relays for the testing, whereas the latter testing bench deals with 8 relays, two for each pneumatic piston. The advantage of the 5/3 valves is that they allow more precise control of the pneumatic piston movements. The 5/2 valve can only allow the pneumatic
pistons to fully extend or contract with its one relay either allowing air into one side of the pneumatic piston or the other. The 5/3 valves allow the pneumatic pistons to be actuated to any desired length within its range using its two relays which separately control the extension and contraction through dedicated airflow canals. When both air inputs of a pneumatic piston are activated at once the equal pressure allows a rigid and rapid halt of the pneumatic piston’s movement, with only a slight response delay. This ability is necessary for the end-result in order to allow finer movements for a more functional, fluid and efficient walking sequence. Testing the two legs with the 5/3 way valves equipped resulted in very responsive and fluid motions, even under load. The 5/3 way valves were tested with abrupt halts of the pneumatic pistons and showed very slight response delays of around 300 ms. Additionally, the same fatigue test done previously was repeated and did not result in any issues.

(More information on 68HC912, 5/2 valve, 5/3 valve, fatigue test can be found in the “additional information” section)

4. Results

After extensive research, design, building and rigidity testing, the resulting leg performed exactly as it was intended to, providing a proper and precise “rowing-like” motion, with slight delays (300 ms) in abrupt halts from the 5/3 way valves, though this has been deemed negligible. Additionally, the tested legs showed no signs of weaknesses or failure throughout the durability tests, confirming the rigidness and reliability of the legs built.
Since the legs had been designed and tested the other two legs were built and tested as similarly as possible and then when approved, the project could move on to the next major part of the machine.

IV. Frame/chassis and housing

The next part of the machine to be built is the frame, or chassis. Note that this wording is taken directly from the terminology of motor vehicles, wherein the underpart that houses the wheels and its mechanisms is called the chassis, although in this case the chassis houses the leg mechanism, rather than wheels.

The purpose of the chassis is not only to accommodate the legs’ mechanisms but also to provide space for the pneumatic equipment, the electrical equipment and the 68HC912 microcontroller. All should be in a protected and compact form. As the machine is likely sustain physical shocks it is important for the chassis to provide a type of housing for the more sensitive parts of the control mechanisms such as the microcontroller and the valves.

1. Design

Similar to the design of the legs previously done, a number of important factors need to be kept in mind when designing the chassis of the machine:

- The chassis must be robust and able to withstand significant forces from most if not all directions (more on this in “frame/chassis results”). In order
to meet this criterion, the factor that should be considered is the material used to build the chassis. There was a great array of useable and easily obtainable material to build the chassis, and a number of these materials were considered such as hollow aluminum bars, metal rods, wooden beams, etc. Ultimately the material used for the final build was hollow steel support beams, with a thickness of 3mm. The material chosen was carefully considered for its durability and robustness. The weight was thought to be a potential issue though as it will be noted further on, the mass of the material chosen would not be an issue.

- The chassis must not exceed a certain mass that the legs cannot viably carry. The legs have a maximum carrying capacity which must not be exceeded as a total mass of the chassis, the equipment resting on top of it, and the horizontal pneumatic pistons A attached to pneumatic pistons B. It must be noted that pneumatic pistons B are the only pneumatic pistons carrying the entire mass of the full machine, as well as any potential object set onto the platform. In order to determine the maximum carrying capacity that the platform could potentially carry, a series of calculations can be carried out based on the pneumatic pistons’ characteristics. Using basic physics formulae outlined in the appendix the following results are found, assuming that the pressure received by each pneumatic piston is equal at around 400 kPa (recommended operating pressure by John Boulton (Boulton 2016)):
  - Pneumatic piston type A: F = 1040 N, m = 106 kg of carry capacity per pneumatic piston
- Pneumatic piston type B: \( F = 1720 \text{ N}, m = 175 \text{ kg} \) of carry capacity per pneumatic piston

Note that the machine has two pneumatic pistons of type A and two of type B used to carry itself, resulting in a carrying capacity of \( 106 + 106 + 175 + 175 = 562 \text{ kg} \). In its weakest instance, meaning that only three legs are touching the ground with two pneumatic pistons of type A, the carrying capacity drops down to \( 106 + 106 + 175 = 387 \text{ kg} \), in perfect conditions, though a lot of factors can change this value but for simplicity it will be safe to assume a rounded down value of around \( 300 \text{ kg} \) of carrying capacity in its weakest instance. The platform is therefore expected to have a very high carrying capacity; the design of the chassis is highly unlikely to exceed this value. The actual carrying capacity of the final design will be determined once the overall mass of the platform is determined.

- The chassis must provide a reasonable surface area for objects to be set upon, as it should potentially be meant for object transport. To accommodate for this design criteria, the width and length of the platform is made to be \( 500 \text{ mm} \times 1000 \text{ mm} \), deeming it to be a proper platform and allowing a significant amount of surface area to work with, as well as adding a great amount of tilt resistance, preventing the platform from tilting on its side, an issue that arose with Shiqi Peng’s robot-dog project (Peng 2006) in the engineering faculty.

- The chassis must provide a proper support for the legs’ mechanisms. The legs are held onto the chassis purely from their pivot points, as seen in the figure 10 below (circled red), therefore the chassis must have
those four points of contact in order to accommodate for the legs, at very precise measurements. The pivot points were measured and represented in Figure 11. With these four pivot points in mind, a variety of chassis designs were thought of (Figure 12):

![Figure 10: hinge positions on test build](image1)

![Figure 11: hinge distances](image2)

*walking machine, side view of leg hinge placements*
The first design was initially the most favorable, as it was simple in build and design compared to the other designs. After extensive consultation, research and advice from John Boulton (Boulton 2016) a new design was thought of which utilizes far less material, allowing a simpler build as well as reducing the weight of the chassis. The platform should be able to carry significant weights, but it is still favorable for the machine to be light enough for any one student to carry around fairly easily in its inactive state. The final design can be seen in Figure 13. The top view is shown in Figure 14. The red arrows show the locations of the pivot points for all eight pneumatic pistons.

Figure 12: considered chassis designs
The initial dimensions were of 1000mm length by 500 mm width, though this had to be changed slightly due to the two horizontal pneumatic pistons’ chambers clashing due to the lack of space. The length of the final design is therefore of 1050 mm, with the same width of 500 mm. The full details of the dimensions of the chassis can be found in the appendix.
Additionally, as previously mentioned the chassis must safely house the more sensitive equipment, though this was less important than other requirements. The testing of the control equipment, similarly to the testing of the legs, was done on a temporary test bench, a wooden platform where all of the equipment was secured, screwed down and strapped on. The test bench was initially meant as a temporary support while a better support would be introduced later on, though the test bench proved to be sufficiently robust for the final build. The test bench will therefore sit on top of the chassis, with a width of 450 mm in order to fit and close the gap in the middle of the chassis, creating a proper platform. The control components are laid flat onto the test bench, and the housing for these components will enclose the entire test bench, possibly made of a tough see-through plastic in order to be able to still see the electrical and pneumatic components while effectively protecting the potentially sensitive control equipment, as this is primarily a display focused project. Note that at the end of the thesis time the housing shell has not been made yet, though it would be advisable as future work for better protection of the more sensitive components.

The final design considered all of the important criteria mentioned previously for the chassis design, taking into account durability, weight, material, leg support and platform dimensions. This final design was then approved and sent to be built.
2. Build

The measurements of each part of the chassis were sent to be used for the frame build. The build was fairly straight-forward, eg, The metal support beams used have a width of 25 mm and a height of 50 mm, with a thickness of 3 mm and mass of 3.07 kg/m. Because of the size of the metal, the parts were welded together for better durability. The welding on the corners of the chassis was done diagonally (Figure 15), in order to cover a maximum surface area, allowing greater connection strength.

![Welding point](image)

Figure 15: welding point for stronger bond

The chassis took about one week to build, and ended up weighing around 16 kg. Once this was done, the four legs were slotted into the chassis using long bolts and fit perfectly into the allocated spaces. Lock nuts were used to prevent the bolts from loosening from potential vibrations when moving around.

3. Results

The legs were held rigidly to the chassis so could easily pick up the chassis and the horizontal pneumatic pistons attached to them when tested. This confirms
correct design calculations. Now that the majority of the heavy part of the machine has been built and assembled, the carrying capacity of the platform can be calculated:

- The total mass of the chassis is: 7.3 kg
- The total mass of the four horizontal pneumatic pistons is: 5 kg
- The platform is therefore able to support a total of: \(562 - 12.3 = 549.7\) kg with its four legs on the ground, which includes the weight of the platform and legs.

Additional calculations of this section can be found in the appendix (page 70). These calculations are based on perfect conditions; several factors can alter the carrying capacity such as leaks in the air canals, irregular source pressure, etc. Additionally, upon approaching the maximum carrying capacity of the platform the legs’ connections to the chassis are more likely to fail due to the weight rather than the legs themselves, though these connections have not been tested to failure. For now, it is not advisable to reach a carrying capacity of more than half of the calculated (549 kg) carrying capacity, until further tests and measurements will be carried out.

It is important to note that a significant issue arose when the chassis and legs were tested. The problem was that when a leg was contracted the entire machine would tip over towards the lifted leg. This is an important issue because this will gravely hinder any proper walking motion. When this problem was detected the feet were reworked in order to rectify the balancing issue.
V. Feet

With the chassis and the legs of the platform built, it is important to create a proper structure between the legs and the ground. The structure will be feet-like devices. Up until this point, the legs touched the ground with an exposed rounded end, designed for a connection to an additional part. This is a good advantage for the design of the feet, allowing a more natural attachment between the foot and the leg.

1. Design

As with the previous design tasks, there are several traits to consider regarding the foot, design traits that must be met and tested in order to guarantee proper function of the overall project. The foot designed must firstly be able to withstand great forces without bending or losing its shape, or revert to its initial state without any damage (rubber for example changes shape due to forces but reverts to its initial shape), with a certain amount of elasticity; it must be resistant to its compression. This aspect revolves around the material used. The feet must also add stability to the machine in order to prevent any tipping over, as it has been determined previously that the machine has balancing issues. Additionally, the foot must provide proper grip to the ground which in turn can provide proper traction to propel the machine forward effectively during its walking motions. Additionally, the foot must be properly secured to the leg, allowing great forces to be exerted to the foot/leg connection without any fear of breakage. The foot must also possess the ability to sense the contact to the ground effectively, using a type of sensor which reliably detects the ground at different contacts angles, as the foot will be positioned differently at different instances; this aspect must be extremely reliable as it will allow greater control
of the leg movements, notably in uneven terrain. The Figure 16 shows the different angles that the foot can come in contact with the ground, and therefore must be adaptable to these different scenarios. The contact arc should roughly be around 60 degrees.

![Diagram of different angles of legs](image)

*Figure 16: different angles of legs*

A number of design ideas were researched and tested to meet the criteria. Some were realized and fully tested as follows:

**a. The ball foot design**

The first design revolved around the idea of a spherical foot. The reasoning behind this was due to the fact that the leg would be extending down onto the ground at different angles, and therefore the foot needed a non-angular dependent contact shape. Several different materials were considered for this build, mainly materials of elastic nature with shape-retaining features, such as foam, hard rubber, soft rubber, etc. Ultimately, a fully sealed pipette ball was used as a temporary testing device. A hollow sealed tough rubber ball would fit
the requirement of durability, shape retention as well as ground grip, as rubber tends to be a relatively non-slippering material. In terms of the sensing mechanism, a variety of ideas were thought of, utilizing different devices such as proximity sensors, push buttons, limit switches, among others. A concept was designed which utilizes the elasticity of the rubber ball, which can create a contact when compressed. The schematic can be seen in Figure 17:

![Figure 17: ball foot design](image)

The sensor concept provides a contact to ground the signal to the 6812 microcontroller’s digital input, by creating an electrical path from the 5 V power supply to the conductive sheet lining the inside of the hollow rubber ball, and to the conductive metal rod within the rubber ball, then finally reaching the microcontroller’s input pin. The key to this sensor concept is the interaction between the conductive sheet and the conductive rod, allowing the current to pass through only when the ball is compressed. It must be noted that this circuit
will only work reliably if there is a sufficiently large pull down resistor. The conductive sheet allows a sensor model that can be interacted through various angles of force exerted onto the rubber ball, allowing a non-angle dependent sensor to be created. In theory, this concept was a good idea; the sensor concept was built and tested to check its reliability and efficacy. However an issue occurred with the mounting of the foot: the leg did not provide any sufficient support for a rubber ball to be securely attached to it. As great forces would be exerted to the foot/leg attachment this was an important aspect that could not be poorly implemented. Additionally, the compression of the ball would be dependent on the amount of weight put onto the platform, meaning that at greater weights the support of the entire platform would depend on the conductive rods, which were not innately designed to support any excessive amount of weight. Additionally, the ball shape did not provide any additional stability towards the overall machine’s balance. Because of these reasons the ball foot design was not considered further.

b. Free-moving flat foot design (with iterations)

Another foot design that was investigated took into consideration the already available leg extremity attachment, allowing a reliable way of securing the foot to the leg. The design idea consisted of a metal plate slotted to the leg attachment through a small metal rod, as shown in Figure 18.
With a sturdy enough metal, this design could potentially be durable enough as a final build. The loose slotting of the foot lets it suspend above the ground and point downward while the leg moves at different angle. Additionally the flat-footed design of the foot stabilizes the overall build, possibly providing enough stability to correct any balancing issues. Although this would be suitable, the design does not have any sensing ability for the contact to ground, though this design can be used as a basis for future iterations. The extended concept of the design involved adding an additional mechanism under the existing plate. Many different types of mechanisms were considered, researched and tested for efficacy. Ultimately, a few design concepts stood out, which can be seen in Figure 19.
The different designs utilize different principles in their function, but both use a mechanical push button for the purpose of the ground sensing. A number of different sensors were considered such as a proximity sensor, though mechanical sensors have the advantage of reliability when set up properly. For this reason a mechanical sensor was chosen to be used. The first design idea utilizes a spring in order to dampen the force from the weight of the platform allowing the push button to be pressed (Figure 19) without actually damaging the push button from excessive weight, which means that the exact spring’s stiffness must be calculated based on the weight of the platform in order to determine how far down the spring will compressed (see Appendix). A major disadvantage behind using a pushbutton-spring design would be the involvement of varied weights placed on the platform; the push-button itself may be damaged if excessive weights are placed on the platform due to an over compression of the springs.

Another design idea revolved around a clamp-like design, which utilizes a door hinge in order to connect the two metal plates together. Upon pressing the ground the clamp would then close and allow the push button to be pressed (Figure 20). Unlike the spring-push button design the clamp-push button design incorporates a rubber block that prevents any excessive force onto the push button by effectively stopping the clamp from closing any further, protecting the push button regardless of the amount of weight put on to the platform. In order to stop the clamp from extending more than a desired amount, a string is also added in order to keep the two metal plates at a certain maximum opening angle. In theory the clamp concept seemed viable on smooth flat terrain, though may show weaknesses in reliability on inclined terrain, possibly putting it at a
great disadvantage in sloped situations. This design was not chosen due to the uncertainty of reliability of sensing contact to ground. Whilst this design was not considered, further tests into the concept as well as continued iterations may still be carried forward in order to check for efficacy of the concept. After extensive considerations of the different designs, concepts from both designs discussed above were incorporated and utilized in a new design, which can be seen in Figure 20.

![Figure 20: final foot design](image)

The concept uses both springs and rubber blocks in order to dampen the force acted onto the foot as well as preventing excessive force being applied onto the push-button, and string/wire to hold the mechanism together.

Using Hooke’s Law (Britannica 2011) it was possible to determine the necessary metal spring in order to reasonably dampen the compressive force of the platform onto the foot. Hooke’s law states that the force needed to
compress a certain spring by a certain distance is proportional to that said distance, giving the equation of:

\[ F = K \times X \]

K being the spring’s characteristic coefficient that is to be found. Using the formula, a reasonable coefficient value determined would be 15, which would ideally satisfy the design, taking into account a 2.5cm compression travel, assuming that the rubber blocks have a thickness of 2 cm.

After considerations of the latter design, there did not seem to be any major flaws. The design provided the necessary durability in terms of downward compressive force as well as the foot to leg connection. Additionally, the foot can reliably provide sensory feedback for the contact to ground, adding a sheet of rubber under the foot allowed the necessary grip to the ground to provide traction. Finally, the flat-foot design works in favor of the stability of the overall machine, providing more stability in order to balance the machine, which in turn prevents it from tripping over. The design was therefore approved and built accordingly.

2. Build

The build of the pneumatic platform’s feet was fairly straight-forward: the parts needed were of common commodities, adding to that the aid of John Boulton for more skilled work such as the precision cutting of the metal plates; the build of the foot was reasonably simple. The foot was assembled using pop rivets and heavy duty glue, the rubber blocks consisted of a 20 mm thick layered
rubber, with 100 mm x 100 mm metal plates held together with thick nylon string. There were a few design changes along the way when building the first foot. After careful consideration and complications in design, a few design changes occurred through the building phase as well as the later testing phases. After some consideration, the springs used were decided to be removed due to the specification of the springs as well as the difficulty in mounting them onto the rest of the foot. The strings should suffice in keeping the layers of the foot together and the rubber blocks to dampen the force exerted onto the foot, resulting in the slightly modified build shown in Figure 21. After being built, the foot must be tested for reliability.

3. Programming/testing

After a prototype foot had been built, it was necessary to test it for proof of concept. An initial test consisted in repeated compression of the foot through repeated force application, similarly to the initial test of the leg but with an addition of a mechanical switch triggering. This test is similar to a fatigue test (R. 1949) (not until failure of the device), allowing the foot to be compressed...
repeatedly over an extended period of time in order to test the durability of the foot. The durability test also involved the push-button triggering within the foot which was wired to the 68HC912 microcontroller in order to capture each instance of the button being actuated. The idea is to test the reliability of the sensor design with the microcontroller. The leg was setup to extend on to the ground every 5 seconds with a 2 second pause and then retract, cycling through this sequence for 4 hours. The results were very satisfactory. The push button was pressed every single time, without missing a cycle. To further test the push button, a similar test was constructed where the leg would extend down until the foot detects the ground, then retract in a continuous looping cycle. This cycle was run for another 4 hours and successfully cycle during the entire duration without stopping, confirming 100% reliability of the foot sensor.

After proving the reliability and durability of the foot design, four more feet were made in order to accommodate for the entire walking platform.

4. Results

A number of feet designs were looked into, ultimately a combination of a number of different concepts were used in order to build a durable, functioning and reliable foot for the walking platform. It is important to note that the feet made are merely test feet and although they function correctly, were not built with a long term lifespan in mind. Therefore more durable and better built feet should be made for a final build, utilizing the same design. For the purpose of this project the test feet will suffice.
If more time was put into the project, more durable feet would have been developed utilizing the same design. This would have been done by using better materials and components.

After being bolted on the feet, the overall build was tested through the individual movement of the legs. The results showed great reliability in ground detection as well as improvements in the overall balance of the machine, though the stability problem was still not fully corrected. Because of this, it was decided for the feet to be again slightly redesigned in order to provide even more stability to the overall machine. The foot’s lower metal plate design was extended in order to provide a wider stability foot, shown in Figure 22.

![Diagram of the modified foot design](image)

**Figure 22: final foot design, 2nd reiteration**

The modified design added a lower metal plate that extends to a width of 20 cm x 10 cm and points inward towards the machine. Adding this extension improved the machine’s stability by compensating for the imbalanced weight distribution. This addition allowed the overall machine to have a more rooted stance, though this was done much later during the project after stability issues
were noticed during the initial walking tests. The machine’s stability will be discussed in greater extent in a later section.

The pneumatic machine’s foot was successfully designed, built and tested. Although the feet have been made and bolted on. Better feet must be built in the future for longer term durability. The majority of the overall hardware build has been completed and assembled, leaving only the control components of the walking platform to design.

VI. Control hardware: Pneumatic and electrical setup

The majority of the overall hardware was designed, built and tested, the next step in the project was to allow the control and monitoring of the built hardware, using an array of control valves, relays and 68HC912 microcontroller (Motorola 2000). The total parts needed in order to control the machine are 8 5/3 way directional solenoid valves (Festo 2002) (which have 2 control relays each), 16 5V mechanical relays, the 68HC912 microcontroller (Motorola 2000) and the power supplies (24V, 12V and a 5V power supply for the different components).

1. Airflow setup

There are a total of eight pneumatic pistons which need to be supplied with air. Through the testing of the legs, the pneumatic pistons properly actuated using 5/3 way directional valves. Each pneumatic piston is supplied with the air from the same model solenoid valves. Because of equipment constraints, three solenoid valves are slightly smaller. In order to easily understand the different pneumatic pistons’ actuation sequences a comprehensive naming convention was created for these pistons (Figure 23).
The recommended pressure for the functionality of the solenoid valves is from 200 kPa to 600 kPa, the pressure is therefore set at 400 kPa, through an adjustable air supply, for optimal and safe operation of the solenoid valves. In order to equally partition the air supply, a metal air splitter was setup with multiple outputs in order to equally feed each solenoid valve without prioritization. This is a correction to an issue seen previously during the testing of multiple pneumatic pistons in which the unevenly split air resulted in certain pistons actuating more violently than others. This issue arose due to the fact
that although the pressure is the same throughout the system, certain pneumatic pistons drew large amounts of air for a small period of time which reduced the available air for that time, resulting in a lower actuation speed for pneumatic pistons actuating shortly after, as seen in Figure 26.

![Diagram showing air distribution with pistons](image)

Figure 25: even air distribution during final tests

![Diagram showing uneven air distribution](image)

Figure 26: uneven air distribution during initial tests
Figure 26 shows a simplified representation of the initial test bench for the pneumatic control of 4 individual pneumatic pistons. The issue with airflow is present when a pneumatic piston actuates, utilizes a large amount of the air supply for a small interval causing a sudden dip in air pressure, resulting in a slower response for a small amount of time. This issue is reduced by equally splitting the airflow feeding into each pneumatic piston, as shown in Figure 25.

The pneumatic setup controls the individual pneumatic pistons through the following succession: The air input feeds into an 8-way divider, each feeding into respective 5/3 way directional valves, which in turn feed into both sides of each pneumatic piston. Each valve is equipped with two 24V relays that can be triggered and allow the air to flow into one side of a pneumatic piston. When the other relay is triggered the air is fed to the opposing side of the pneumatic piston. When the air is fed into one side of the pneumatic piston chamber, the difference in pressure between the two sides of the chamber allows the movement of the pneumatic piston by expanding the side of the chamber with the highest pressure. Note that when both relays are activated simultaneously the pressure on both sides of the pneumatic piston chamber is equal, which results in the pneumatic piston position to be held rigidly in place. This rigid hold is fairly reliable, although the gas on both sides are compressible therefore excessive force on one side of the piston can move the piston slightly, though this has been deemed negligible for now. Figure 27 describes the pneumatic pistons’ control description.
2. Electrical setup

The electrical setup of the pneumatic walking machine is primarily present for the control of the pneumatic valves discussed earlier, as well as for the feedback of the array of sensors connected to the machine. The different components for the control require different voltage levels in order to properly function. The pneumatic valves function using 24V supply, the mechanical relays function using 5V supply and the 68HC912 functions using 12V converted down to 5V using a voltage regulator for a smoother voltage input. Additionally, the added keypad and LCD screen are powered by 5V inputs, though these are taken from the microcontroller itself. The heart of the control of the pneumatic walking machine is the 68HC912 microcontroller. Powered by a 12V supply, the microcontroller triggers each of the 16 5V mechanical relays.
which in turn provide power to each 24V relay controlling the solenoid valves. The reason for using mechanical relays is for its visual aspect: the walking platform is a showcase project, which should be visually understandable to a certain extent. The relays provide a visual indication (red lights) of what is happening during its movements. It should be noted that transistors would have been a more reliable choice for this function. Additionally, the microcontroller also handles the input of the different sensors that have been and are planned to be added to the walking machine.

3. Results

With the pneumatic and electrical setup complete, the board was then tested: the three supplies were activated, the 68HC912 microcontroller was successfully connected and basic output control code was tested to trigger the array of mechanical relays. The 24V relays are equipped with indicator lights showing their correct operation, which triggered accordingly in parallel with the mechanical relays. The air supply was then connected to the machine and the same tests were conducted to confirm the correct control and operation of each individual pneumatic piston actuation through each mechanical relay switching. The results were favorable though it must be noted that certain pneumatic pistons actuated less vigorously than others. This was initially thought to be due to the presence of two types of solenoid valves being used, four smaller valves and four larger sized valves. This may not necessarily have been the issue because only a couple of pneumatic pistons actuated differently. A quick test was conducted wherein different valves were used to actuate the same pneumatic piston showed that the pneumatic pistons still actuated similarly,
possibly confirming that the valves are not to blame but rather either the pneumatic pistons themselves or simply the air distribution. An issue arose during the testing of each pneumatic piston where a pneumatic piston contracted but refused to extend, pneumatic piston RC (Figure 23). The pneumatic piston was tested using a different solenoid valve and actuated with no issue, meaning that the issue was not to do with the pneumatic piston but rather the solenoid valve not actuating correctly, possibly due to a sort of jam in the airflow mechanism. The solenoid valve was therefore replaced with a new one, resulting in five larger solenoid valves and three smaller solenoid valves. As a side note, the smaller solenoid valves are ones that have been used in the past and found in equipment storage therefore may not function perfectly, whereas the larger solenoid valves have never been used before; this justifies the replacement of the solenoid valve as it was a smaller, used valve.

Figure 28 shows the actual setup of the control components of the walking machine, mounted onto a wooden board and separated by a red horizontal line with the pneumatics at the bottom and electrical parts at the top. The 68HC912 microcontroller can be seen circled in red. Figure 29 is a more comprehensive guide for the understanding of the interaction between different components of the system, with a color code designating the electrical components, the pneumatic components as well as the communications components. This diagram is to be referred to when looking into the wiring as well as for any intended additions to the control. Note that although three sensors have been included in the diagram, the leg angle sensors as well as the leg extension sensors have yet to be installed in the machine, but are an intended feature. More on this will be discussed further on.
Figure 28: control setup, pneumatic and electrical
Figure 29: Visual diagram of pneumatic and electrical setup
VII. Overall build

The entirety of the machine's hardware has now been designed, built, selected, mounted and put together. The control equipment was mounted and connected to the pneumatic pistons, allowing full control of the platform's legs. 68HC912 is connected to using an RS232 cable, though wireless communication is a considered future addition. Each part of the machine was previously tested individually therefore they should function accordingly though the combination of all the parts put together was not yet tested for full functionality. In order to efficiently do so, a combined functional code was written in order to fully utilize all of the different interacting parts of the machine.

1. Programming

In order to control the leg mechanisms the 68HC912 microcontroller needed enough output control pins to actuate the array of the mechanical relays. There were a total of sixteen mechanical relays. The test board of the microcontroller was equipped with 8 inputs and 8 outputs, setup as ports P and T (Motorola 2000), though this can easily be modified. In order to more easily fit the microcontroller, the test board was removed along with the Darlington arrays. This action can be risky as the Darlington arrays were there to protect the microcontroller, though as long as the wiring is checked to not feed a voltage that is too high to the microcontroller there should not be any issues. Ports P and T were fully enabled as 16 digital outputs for the control of the mechanical relays. Port S was also enabled as digital input pins for the reading of the feet sensors, which amounted to 4 input pins. Additionally, 2 analog read pins were enabled and intended to be used for the leg angle sensing, though are currently unused. Additional digital input pins will need to be enabled for the leg
extension and contraction sensing, as well as possibly the leg angle sensing, though more detail on future sensing capabilities will be discussed further on.

The code of the walking machine is currently divided into two major blocks, the sequence of extensions and contractions of individual pneumatic pistons and the continuous reading of the sensors. Currently the two code blocks do not directly interact with each other: the feet sensors detect the contact to ground and send a signal each time, while the movement sequence activates and deactivates the pneumatic pistons in the correct order so as to create a type of gait of the machine, though this is purely timing dependent. This sequence of motion was written through trial and error, observing and predicting the necessary amount of time needed for each pneumatic piston to move sufficiently. It is however a future goal to have the motion sequence dependent on the sensory feedback, though there is currently not enough feedback to provide enough information for an “intelligent” gait. The feedback of the various sensors along the walking machine was to be monitored using tasks in order to be able to run multiple loops at the same time. This would allow the reading of an array of sensors while simultaneously executing the sequence of movements as well as provide an emergency stop button in case of any incident.

2. Testing

With a first draft of a walking sequence written, the machine was to be tested for its first steps: The platform successfully lifted up by the extension of pneumatic pistons LA, LD, RA and RD, although with an oddly slower extension speed in pneumatic piston RA. The feet sensors were then tested by lifting a foot and pressing it against the ground and testing their reliability, which proved to be successful. After the sensor test, the gait was to be tested next. The first
iteration of the walking sequence relied on a sequence mimicking the gait of an animal, such as a dog (David M. Nunamaker 1985). This seemed like the most logical approach, though after a quick test it was apparent that an animalistic gait was not currently possible due to its limited stability: This aspect was an issue that unexpectedly arose during the testing of the full machine’s walking motion. During the design of the chassis, a fair width was given to the machine in order to counteract the possibility of the machine tipping over. What was not considered was the fact that the limited leg movement in its degrees of freedom, as well as the fact that the momentum swing generated through the outward movement of the legs would tilt the machine towards any one raised leg, causing it to lose balance and fall over.

3. Results/issues

The overall machine is a sturdily built, 70 cm wide, 105 cm long and 40 cm tall walking platform capable of potentially carrying around 500kg of weight. A great majority of the tasks set out were completed, notably the task of creating a walking machine capable of carrying loads, as well as a starting point for sensory feedback which was expected to be achieved. The resulting product functions properly, though not as well as it was hoped for. The walking machine, though walks, does so at a very slow pace due to its very limited motion arc of around 60 degrees, coupled with a leg length of around 40 cm. It must be noted however that the intention was not to create a fast walking machine but a stable and sturdy one, capable of steadily and surely move from one point to another.
Stability issues

Another point was raised during the resulting tests of the overall build, which was the overall stability of the machine. Due to a varied number of design factors the resulting machine proved to be fairly unstable during its walking locomotion. The design choice of a wide machine proved to help stability though only when four legs were touching the ground. When one of the legs was raised the stability issues start to arise and even more so towards the machine’s side with pneumatic pistons of type B, due to their greater weight. When one pneumatic piston B is raised the machine would trip over towards the same raised leg. This issue can be analyzed on a physics perspective by looking at the diagram in Figure 30, a drawn red line can be seen.

![Diagram](image)

Figure 30: balancing issues representation
This line represents the two furthest points of stability between its opposite feet tracing a line of standing stability. The center of gravity (Hall 2015) can be roughly estimated during its standing position, seen as the red mark. When any weighted part of the machine is shifted either on the x, y or z plane, such as a leg movement, then the center of gravity is also shifted. Determining the new center of gravity shows that it has shifted past the line of stability determined earlier, confirming the instability in its walking motion. There are a number of different ways to deal with instability:

- Modified gait: By moving the other legs to specific positions it is possible to add stability to the overall machine. As the feet are the points of contact to the ground which determine the machine’s stability, it is possible to reposition each foot in order to provide a more balanced stance though this will likely decrease the possibility of an animalistic gait, leaning more in favor to a robotic and systematic walking locomotion. In order to provide more stability, the feet must be positioned inward as close toward the body possible, moving the line of stability away from the center of gravity allowing more room for the center of gravity to be varied without the machine losing balance, as seen in Figure 30.

- Foot redesign: the foot is the direct contact to ground for the machine and can be modified to provide more stability to the overall machine, taking in consideration the placement of the center of gravity as well as the line of balance seen earlier. In fact, following on from the
balance issues the foot was slightly redesigned as mentioned earlier in this report (V. feet, 4. Results). The redesign was tested on the machine and showed slight improvements in its stability by providing a more inward point of stability for certain situations. A more complex redesign of the foot can greatly benefit the overall stability of the machine’s motions.

- More leg movement: As of the end of this project, the leg’s movements are limited, allowing forward and backward motion as well as vertical motion, though no outward motion; adding a third plane of movement, a z-plane motion, can provide better movement and gait, which will in turn provide better stability to the overall machine during its walking motion, allowing the machine to alter its leg positions more accurately and favorably to allow a more stable three legged stance. This motion addition can be seen in the diagram below, altering not only the weight distribution but also the stability line for a particular raised foot. This functionality addition should be looked into as a future task.

- Redesigned chassis: The current chassis of the machine is very simplistic; it is essentially a rectangle of equal weight distribution. Due to the fact that one side of the machine is heavier than the because of the added weight of the bigger pneumatic pistons B the overall machine’s center of gravity is off-center, meaning that stability in a
three legged stance is harder to achieve when dealing with the heavier legs. Through fairly simple chassis redesign, the weight distribution can be taken into account in order to counteract the heavier legs to correct the center of gravity and adjusting it towards the center.

Additionally, brief ideas were considered to provide a dynamic weight distribution modifier, allowing part of the weight of the machine to be redistributed accordingly for certain situations in order to provide greater stability. It is currently not known how this can be implemented, though further research should be done in this area.

- Weighted feet: adding weight to the feet can provide a more rooted stance which will in turn make the machine more stable, notably for three legged stances. It must be noted that this solution will amplify a different factor which will have to be taken in consideration in order to not create more issues: a greater generation of outer momentum from the feet and legs during outward movements. An easy correction for this issue can be to reduce the speed of the movements by attaching air limiters, slowing the airflow rate into the different pneumatic pistons or possibly an accelerometer to limit the actuation speed.

These different methods can allow a greater stability in the overall machine, which can in turn greatly improve its walking locomotion. Stability aside, the walking platform is a successful project accomplishing its intended goals of a walking locomotion as well as a sturdy, load carrying machine. Because of its
hindered stability, the machine cannot currently properly move objects onto its platform without greatly shaking and tossing around said objects, therefore the predicted 500 kg weight carry is not realizable or testable unless significant work has been continued on the project.

A multitude of sensors were attempted to be attached to the machine, such as potentiometers to monitor the rotational movements of the pivoting of the legs, as well as limit switches to monitor the vertical extensions and contractions of the legs. This task proved to be more difficult than expected due to lack of physical support spaces to accommodate the various sensors. Because of this, the sensors were not implemented at all, excluding the feet sensors.

VIII. Future work/unfinished work

1. Sensors

As previously discussed an array of sensors were planned to be added to the walking platform, though because of time constraints and unexpected delays such as certain task requiring more time than planned, this section of the project was not achieved. It must be noted that extensive research has been done in order to supply the necessary information for the sensor work for any future student picking up the project. There are currently four main aspects of the walking platform that need to be monitored through the use of sensors, which need to be reliable in normal conditions as well as sloped terrain:

- The contact to ground: this sensing ability has already been established using push buttons incorporated into the feet of the
walking machine, and has been proven to be reliable for simpler terrains. The feet sensors have not yet been tested for sloped terrains.

- The multidirectional tilt: this sensing ability is in regards to the balancing and can greatly benefit the machine’s gait through a corrective behavior from sensory feedback. The tilt sensing can be done using either tilt sensors or a gyroscopic sensor. This sensor type will not be properly useable in sloped terrain due to the nature of the measurement: The sensor will detect a continuous tilt from the slope.

- The contraction of the legs: This sensing ability can easily be established through simple limit switches connected to the pneumatic pistons, one for each leg. The sensors would not be dependent to any sloped or uneven terrain. The extension of the legs is not necessary due to the fact that the feet sensors are already detecting the full extension through the detection of the ground.

- The pivoting of the legs: an important aspect to detect and measure is the angle at which each leg is pivoted at. This can be done through the use of a potentiometer connected to the pivot point of the pivoting piston, by which an analog signal would be read, though this may be prone to error as wear and dirt builds up over time. Alternatively the pivot can be detected through a series of roller lever limit switches, essentially detecting the two extremities of the pivot as well as the middle point. This would require 12 roller lever switches in total.

In fact there is a feature found in most limbed animals, called proprioception (Miller 2010). It is the sense of the relative position and angle of the different
parts of the body and the force exerted which allow the adjustment of the animal’s upcoming movement for a proper walking motion. This sense is what defines proper locomotion in animals and what is desired to be reproduced in modern robots, such as with Boston Dynamics’ robots (Dynamics 2016).

The sensors are a big addition to the project, providing continuous information to be fed to the 68HC912 microcontroller (Motorola 2000). This information can be used for the purpose of reactive responses in its walking and balancing.

2. “Intelligent” walking

Once the sensory feedback is established, the information from those sensors can allow the machine to react accordingly to its current status of its various parts. “Intelligent” walking can be established through code:

The “intelligent” walking can allow the machine to react from certain factors and statuses of both the environment and itself. The contact to ground can allow the machine to know when to stop extending its leg, in order to keep the level of the platform even. A tilt sensing ability can allow the machine to know when it is in the process of losing balance, allowing it to correct this imbalance by taking the appropriate countermeasure through leg movements in order to keep the platform leveled. This can be done with a 9 degree of freedom accelerometer (DimensionEngineering 2016). The contraction and pivoting of the legs is monitored for more fluid walking motion, in order to know when the next movement can occur without actuating any leg too early. This code structure can be seen as a simple state machine design, responding to certain sensors
with a leg movement which triggers other sensors and so on, instead of the current timing-based code structure.

3. **Added stability**

As previously discussed, the stability of the overall machine is an issue that needs to be resolved. The machine must ideally stay relatively leveled during its movement from one point to the other. Adding the hardware fixes discussed earlier can greatly benefit its stability. Additionally, stability corrections through the code can also improve its stability: human beings follow a similar principle in walking in the way that a walking is essentially a lean forward followed by a readjustment of the weight distribution through a step movement which catches the person from falling forward (Smith 1891). Similarly when standing a person uses the appropriate muscles and sensory feedback in order to stay balanced in an upright position. This is a desired function in the walking machine. There are actually two types of balancing natures: static balancing and dynamic balancing (Kjaer 1995). Dynamic balancing involves the continuous adjustment of parameters and controls in order to achieve balance and stability, whereas static balancing is the inherent stability that a certain body has due to its characteristics, such as the weighted feet concept seen earlier. A combination of both balancing actions can provide a fully stable and adaptable machine.

4. **Wireless communication**

An addition that can significantly improve the project would be the implementation of a wireless communication: The machine currently communicates through an RS232 communication cable, and although this
works well, is not well adapted to the situation at hand. The platform is meant to move but cannot do so freely when attached to a limited communication cable. Additionally, a similar solution could be looked into for the power supplies being wired as well, though because of the presence of different power supplies additional circuitry may be necessary.

**Safety checks**

A few points had been addressed throughout the report: notably on the carrying capacity, the durability of certain points of the machine such as the leg to chassis connection as well as the feet durability. These parts have been tested to a certain extent, though additional research and testing is recommended in order to know more accurately the capabilities and exceeding limits of the machine’s different parts.

**IX. Conclusion**

The final product of the project is a walking-capable machine with a carrying capacity of around 500 kg. The great majority of the tasks set out were achieved with few issues throughout the project. It must be noted that one of the bigger aspects of the project, the balancing and stability, is still ongoing work. Although the machine is capable of locomotion, it currently does so through a timed sequence of control which actuates pistons in a set order. The ideal goal of the project in the future is to allow the machine to independently move and walk through a series of feedback responses from the sensors of the machine itself. This idea of sensory feedback is a common trait seen in biological creatures, allowing the stance and movement to be a corrected action from the machine itself, similarly to the balancing of a human during its stance and its
walking motions. The next logical step in the project would be to continue work on the sensors and research into dynamic balancing in biological quadrupeds and robotic machines.

X. Appendix/Additional information

1. Force to width relation in regards to pressure

When considering any kind of linear pneumatic piston movement, it must be noted that two factors are taken in consideration in order to determine the force of a pneumatic piston: The pressure input into the pneumatic piston and the width of the chamber inside of the pneumatic piston:

- There is a direct relation between the force a pneumatic piston generates and its inner width. The pneumatic piston’s width can be determined through basic geometrical calculations, whether it be a cylindrical pneumatic piston or a rectangular pneumatic piston. In this case the pneumatic pistons at hand are cylindrical, meaning to find the width is a simple matter of using the formula:
  \[ A = \pi r^2 \]
  Keeping in mind that A is the area of the cylinder’s base in m\(^2\) and r is its radius in m. The greater the area of the base of the cylinder, the higher the generated force.

- The pressure input into the pneumatic piston also varies its driving force, meaning that the higher the pressure the higher the generated force. The pressure is in Pascal.

The relation between the force, pressure and area is the following:
\[ F = P \times A \]

Note that these are the only determining factors for the force generated by the pneumatic piston. There is a common misconception that the length of a pneumatic piston changes the force of the pneumatic piston though this is false, the length of the pneumatic piston has no impact on its force.

2. Valve types and functions

A solenoid valve is a type of valve which can be actuated through a solenoid, a metal spring which extends or contracts based on a current running through it (CDindustrialGroup 2016) through the use of electromagnets, allowing or preventing air to pass through certain canals, changing the path of the air flow. Solenoid valves are used for a wide range of purposes and come in very different models and designs. In order to easily keep track of the different solenoid valves available, a naming convention was established to easily understand the capabilities of any solenoid valve (CDindustrialGroup 2016). The naming convention is structured as the following. A first number is designated followed by a forward slash then a second number, indicating the number of available ports on the device and the number of different flow paths the device can be configured to, respectively. The numbers are then commonly followed by either NC or NO, indicating that the valve is either Normally Open or Normally Closed, which is the state of the valve when at rest. Using this convention, saying that a valve is a 4/2 way NC directional solenoid valve means that the solenoid valve is equipped with 4 ports and is configurable to
two different flow states, and that air flow is not possible when at rest since it is Normally Closed.

Two figures 31 and 32 show the configurable function of a 4 port 2 way solenoid valve. The figure on the left shows the extension of the pneumatic piston and the figure on the right the contraction of the pneumatic piston. Note that in this case the exhaust mechanism of the solenoid valve is done through the same exhaust port, port T, and the output ports are denoted as ports A and B.

![Figure 31: 4/2 valve example, extension](image1)
![Figure 32: 4/2 valve example, contraction](image2)

![Figure 33: 5/3 valve characteristic diagram](image3)

Additionally, each solenoid valve comes with a comprehensible diagram showing its available configurations, following a common standard (Festo 2002). Figure 33 shows the configurations of a 5/3 solenoid valve, as an
example. The way of understanding these diagrams is to see the different partitioned sections of it. There are 3 separate blocks in the diagram, which show three possible configurations. The first block shows the possibility of supplying an output while simultaneously exhausting the other output. The third block is the same but mirrored, and the middle block simply shows all the ports being blocked.

Two different solenoid valves were used throughout the project: the 5/2 way NO directional valve and the 5/3 way NC directional valve:

- The 5/2 way NO directional valve is equipped with 5 ports and allows two flow paths to be configured. This solenoid valve was mainly used during the testing of the pneumatic pistons' control, notably during the testing of the leg mechanism. Two of the ports on the device were used as exhausts, one for the air inlet and the other two fed into a pneumatic piston. The two available flow positions differed in the output of the air inlet, changing from one output to the other while simultaneously exhausting any air from the other air canal through the vent ports. The airflow configuration is simply changed through the activation of a connected relay which actuates the solenoid.

- The 5/3 way NC directional valve is similar to the 5/2 valve due to the fact that it also has 5 ports which are the same as the 5/2 valve, though in this case the valve has three available air flow configurations and is normally closed. The three air flow configurations are a normally closed state where the air is blocked from any output port, and the two same configurations as the 5/2 valve where the air can be directed to either output port. Note that the 5/3 valve is equipped with 2 relays, one for
each output port which are both equipped with their own solenoid, and if both are activated the two solenoids allow both output ports to output air. If the two output ports are activated and feed into a pneumatic piston the pneumatic piston will stay rigidly in place due to the equal pressure on both sides.

The 5/3 way directional valve was used for the final build of the walking platform due to its ability to rigidly halt each pneumatic piston in its movement through the additional airflow configuration that the 5/2 valve does not possess; The 5/2 valve is only able to fully extend or fully contract a pneumatic piston.

3. 68HC912 microcontroller

The 68HC912 microcontroller (Motorola 2000) is a microcontroller developed by Motorola and coded in Forth language in the SwiftX programming environment. The microcontroller is connected to a small development board which can be easily expanded for additional capabilities. This microcontroller allows the use of its various different ports for the purpose of controlling or monitoring data through basic digital and analog signals. It is equipped with digital and analog output controls, as well as digital and analog input reads, allowing the development of various different projects with the main focus of learning.

4. Fatigue test

The fatigue test is a method of equipment testing designed to determine the durability and overall reaction of the material or equipment under varying loads. Commonly, a fatigue test is started with a determined starting load, which can be zero, and then increasing loads are applied to the equipment through a
continuous cycle until the equipment or material eventually reaches the point of failure. The fatigue test was exercised on multiple parts and equipment of the walking machine though in a loose way, meaning that only rough checks were done and no precise data was gathered. More precise and rigid testing should be done in the future. Additionally, because of time constraints and inconvenience the fatigue tests run were not exercised until failure. Because of this, a general idea of the materials’ capabilities have been determined though for further and more accurate results the fatigue test could be run again until failure for certain more important parts of the machine such as the leg to chassis connection and the pneumatic piston to pneumatic piston connection, making sure to acquire more precise data which can be displayed on a graph showing the amplitude of the loads exerted onto the tested equipment.

5. Hooke’s law, spring coefficient

Hooke’s law (Britannica 2011) states that the force required in order to extend or contract a metal spring by a certain length designated as $X$ is directly proportional to that same distance $X$. The equation which defines this is:

$$ F = K \times X $$

Where $k$ is a characteristic property of the spring at hand, which can be denoted as its stiffness or coefficient.

During one of the final iterations of the feet design, springs were required which needed to be compressed a certain distance $X$, which was determined to be 2.5cm. With a total machine weight of about 15 kg, a spring characteristic constant could be determined:
2.5 cm travel, X

Weight of entire machine \( m = 15 \text{kg} \)

\[
F = m \times A
\]

\[
F = 15 \times 0.025 = 0.375 \text{N}
\]

Using hooke’s law:

\[
F = K \times X
\]

\[
F \div X = 0.375 \div 0.025 = 15 \text{N/m}
\]

The desired spring characteristic is of 15

6. Animal gait (canine)

The project’s locomotion is desired to follow the gait of an animal, more precisely a canine. The canine’s gait is a complex sequence of movements that can be broken down into a repetitive pattern: taking only in consideration symmetrical gait, meaning the walking, trotting and pacing of a canine, the gait is a mirrored motion of one side of the dog and then the other, as seen in fig 34.

Figure 34: canine walking motion (David M. Nunamaker 1985)
Following this principle, the motion can be considered as the movement of a front foot, followed by the opposite side back foot, then the other front foot and finally the last foot is moved. This motion is a systematic and fluid movement which is coupled with a forward lean in between the two mirrored motions. Currently the machine does not have the proper responsive sensory feedback necessary to follow the canine’s gait, leaving it unbalanced if it is attempted. Note though that this gait would be the most favourable in terms of walking efficiency as a more complex movement when the machine is at a better standpoint.

7. Final dimensions

Chassis: 1050 x 500 x 50 mm (piston A supports are 100mm additional height)

Metal used: 50 x 25 mm

Foot: 100 x 200 x 50 mm

Calculated weight of chassis

Metal weight: 3.07 kg/m

Total chassis’ metal length: 2.4 m

⇒ Chassis weight = 7.3 kg
8. Calculated carrying capacity

Considering pressure of 400 kPa:

- Pneumatic piston type A: surface area of $\pi r^2 = 105 \text{ cm}^2$
  \[ F = P \times A = 1040 \text{ N} \]
  \[ m = F \div A = 106 \text{ kg of carry capacity per pneumatic piston} \]
- Pneumatic piston type B: surface area of $\pi r^2 = 172 \text{ cm}^2$
  \[ F = P \times A = 1720 \text{ N} \]
  \[ m = F \div A = 175 \text{ kg of carry capacity per pneumatic piston} \]
Works Cited


