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Development of an Anthropomorphic Mobile Manipulator with Human, Machine and Environment Interaction

An anthropomorphic mobile manipulator robot (CHARMIE) is being developed by the University of Minho's Automation and Robotics Laboratory (LAR). The robot gathers sensorial information and processes using neural networks, actuating in real time. The robot's two arms allow object and machine interaction. Its anthropomorphic structure is advantageous since machines are designed and optimized for human interaction. Sound output allows it to relay information to workers and provide feedback. Allying these features with communication with a database or remote operator results in establishment of a bridge between the physical environment and virtual domain. The goal is an increase in information flow and accessibility. This paper presents the current state of the project, intended features and how it can contribute to the development of Industry 4.0. Focus is given to already finished work, detailing the methodology used for two of the robot's subsystems: locomotion system; lower limbs of the robot.

Keywords: *Robotics, Mobile Manipulator, Service Robot, Mechatronics*

1. INTRODUCTION

Recent developments in neural networks have allowed the achievement of more robust, versatile and easier to program solutions to many problems tackled in robotics. Such problems include trajectory finding, movement optimization, sound, speech and dialogue recognition, object recognition using computer vision and decision -making skills [1]. Many specific solutions have been developed and optimized to deal with each of these problems individually. The purpose of this project is the creation of a mechanical platform, the anthropomorphic mobile manipulator, which can incorporate and take advantage of these solutions, merging them in a single robot, benefiting from the interaction between technologies.

A sketch of the robot's appearance is shown in Figure 1. Although an anthropomorphic structure is presented, wheeled locomotion was chosen opposed to legged locomotion due to its power efficiency and faster running capability in a regular terrain [2].

When developing a robot, the choice must be made regarding a task-focused robot or a versatile robot. Task-focused robots are often superior regarding that specific task, while versatile robots have the advantage of a higher market-size and wider variety of application. Versatile robots often have long development cycles, with constant newer iterations being made with constant improvements learning from the implementation of the previous one. For the mobile manipulator (CHARMIE), a versatile robot approach was made. Such approach carries the disadvantage of some design choices not being able to be optimized for all possible tasks and work environments. The versatility in an early stage of design allows a future specialization of the robot, changing parts of the robot's structure and architecture for a specific task of the interest.

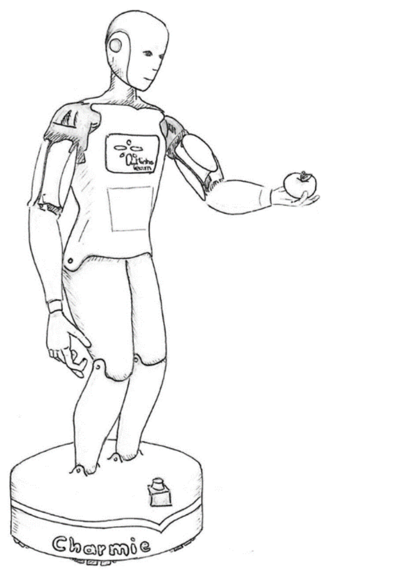

Figure 1. Conceptual sketch of the anthropomorphic manipulator (CHARMIE) made by Inês Garcia

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This article will focus mainly on the suspension system and the lower limbs of the robot. Usage of modularity in robotics is becoming more common, being the coupling of components and subsystems from different robots increasingly common. The aim is for the developed subsystems to be, after testing, optimized for such interchangeability and modularity, allowing usage of this system for any robot, which would benefit from it. Work on these two systems results in the following main contributions:

- **Development of a simple suspension system for four-wheeled omnidirectional locomotion systems**. The simplicity, small size and ease of replication of the adapted MacPherson suspension system allows it to be adapted to other robots. This style of locomotion is very widely used [2], from simple to complex robots, meaning this suspension system could also have a range of applications. Usage of different springs and materials can increase or decrease the robustness, rigidity and strength of the system.
- **Development of an anthropomorphic looking elevator mechanism**. Human-like looks are often searched for in human-robot interaction, being proved that humans prefer working with human-like robots and are a lot more willing to accept them [3]. However, such design choices are often accompanied by a high increase in complexity of mechanical, electronic and control software of the robot. The proposed design of the robot's legs allows an elevator mechanism (commonly used in mobile manipulation) to have an anthropomorphic look without increasing the electronic and control software complexity. Although the complexity of the mechanical system increases substantially in this iteration of the solution, a redesign based on the same mechanical principles is being made which will result in a simpler and more reliable solution with a significant increase in robustness. The aim is for the benefits of choosing this style of elevator mechanism to outweigh its inevitable disadvantages.

Regarding the state of the art, several areas, with each their own focuses, have been working on the develop0ment of new technologies which can be applied in robotics [4,5], especially related to neural networks [6–8]. The main contribution of this project, and this paper, will be the integration of all these new technologies in a single working product, facing all challenges related to their implementation and interaction. The aim is to leave the conceptual stage and achieve an optimized, ready to be sold in the market product. The development of bioinspired robots is highlighted as one of the grand challenges of Science Robotics [9]. Within this challenge, effective integration and embodiment of bioinspired sub-systems to perform system level-behaviour and the venture of bioinspired robots beyond laboratories and into the world are two of the goals which will be addressed in this project [9].

1.1 Features of the Robot

The first step for designing the mobile manipulator is the establishment of features and requirements. The main features are:

- Object recognition with computer vision.
- Sound and speech recognition
- Speech production
- Autonomous decision making based on neural networks
- Locomotion with four omnidirectional wheels
- Obstacle avoidance and trajectory finding
- Object interaction with two anthropomorphic arms and hands

Listing these features, it is possible to determine the needed software and hardware modules (Figure 2). Each of these modules will be worked on and optimized independently, always taking into account their posterior integration and communication with other modules.

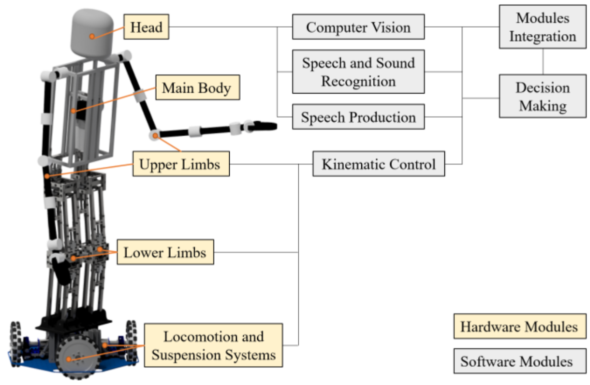

Figure 2. Schematic representation of the robot's hardware and software modules

Starting with the hardware, the robot was divided into five modules:

- Locomotion system: Allows movement of the robot around the environment, removing the limitation of having it in a fixed position, increasing the range of uses for the robot. The locomotion system uses four omnidirectional wheels and requires a suspension system. This choice was made regarding the predicted work environment of the robot, large indoors environments such as industrial pavilions.
- Suspension system: Due to usage of four omnidirectional wheels, a suspension system is required to guarantee continuous contact of all four wheels with the floor, as well as guarantee smoothness of operation.
- Lower limbs: A mechanism with only 1 degree of freedom which allows a squatting movement of the robot, maximizing its workspace and allowing interaction with objects on the floor.
- Main body: Structural system that supports the head and arms, as well as house the main electronic components.
- Head: Structural system with three degrees of freedom which houses the sensorial components that gather video and sound information.
- Upper limbs: Two anthropomorphic arms, with seven degrees of freedom each, for object manipulation and machine interaction. Each arm will have a robotic gripper in the form of an anthropomorphic hand with five degrees of freedom, one for each finger. Each of the fingers

should also include pressure sensor for programming and training of the neural network responsible for the robot's kinematics.

Regarding the software, six modules can be identified:

- Computer vision: Using cameras placed on the robot's head, computer vision will be responsible for object recognition using machine learning. The robot must be able to determine an object's position for both object interaction and trajectory finding. In a more advanced stage, it should be able to recognize buttons and interfaces from the machines it will interact with. Ideally, for maximizing its potential, the robot must have a training period for optimizing its vision for the work environment it will be installed in.
- Speech and sound recognition: Inputting audio from microphones in the robot's head, machine learning will be implemented to train the robot to recognize and interpret human speech. The robot's neural network must be trained in order to recognize basic commands regardless of gender, age or accents. Certain terms, object and machine names can be taught to the robot by crossing information from the visual and audio inputs in a solution like Karlsruhe Institute of Technology's ARMAR III interactive learning of new objects [10]. The robot should also recognize certain sounds such as machine failure or an audible emergency alarm.
- Speech production: Voice is the most common way of communication. By mimicking human speech, interacting with humans becomes simpler. This will also allow the robot to relay messages and orders.
- Kinematic control: The kinematic control of the robot must both consider the locomotion of the robot and the movement of the limbs and head. Movement must be as reliable, fluid and fast as possible. Neural networks in the kinematic control results in a more robust and versatile movement, with the robot being able to apply corrective measures for variations in working conditions, such as joint friction or carrying payloads [6]. Inputting information from the vision module, trajectories for movement must consider and avoid obstacles. The usage of a redundant manipulator (arm with seven degrees of freedom) facilitates obstacle avoidance.
- Modules integration: The software module responsible for transporting information within the robot, filtering it and providing each module with the data required for it to function.
- Decision making: The main brain of the robot, this module will be responsible for interpreting sensorial information and commands received directly, from a database or a remote operator, and decide the best course of action based on that information. The decisions taken will be chosen from a hierarchical pool of relevant pre- determined choices. This hierarchical structure consists of main decisions such as stocks management, machine inspection, interaction with workers, communication or helping in an emergency, etc. where some situations, such as emergencies will override any other decision. Within each of the main decisions, there will be a set of sub-decisions. If the robot choses that stock management is the most important task at that moment, what stocks will it verify? Finished products or raw materials? And which product specifically? Online analysis of the robot's performance while performing these tasks will allow it to adjust internal parameters optimizing the task priority for future iterations. A correct discretization of tasks and sub-tasks will be fundamental and should be constantly improved and updated after the robot begins first works as an autonomous prototype.

1.2 Intended uses and applications in Industry 4.0

With its capability to gather information and interact with humans, machines and objects, as well as relay information remotely, the robot becomes a valuable resource for Industry 4.0. The robot comes as an interface which can upgrade older machines and production lines to a higher degree of connectivity and intractability.

The ability for movement, as well as inputting visual information, allows assembly-line inspection. The robot can count the flow of parts moving through a certain stage of a production line and update that data in real time. This comes as an added advantage in lines where human interaction is involved, which can result in fluctuations in production speeds. The visual input can also be used for stock management. Depending on the organizational logic of a facility and the kind of parts being produced, the robot can check inventory levels, feeding the information to a database. In industry where advanced inventory management is already in place, the robot can act as a verification tool and help aid in the implementation of warehouse management and optimization strategies based on computer simulations as proposed by other authors [11].

Speech production allows the robot to communicate with humans, allowing a bridge between the virtual network and the physical environment. On an advanced industrial complex, the information gathered by machines can be enough for someone to monitor the factory remotely and give orders accordingly. This allows the robot to be a virtual avatar of someone and relay orders from them to the worker. On highly advanced system, the robot and database, together, can be able to determine optimal solutions and manage human resources accordingly. Speech recognition allows a reverse flow of information, allowing anyone from the assembly line to transmit any information into the virtual domain.

Object and machine interaction allows the robot to act as a replacement for other kinds of manipulators or a human worker. Fluctuations in production rates are common in some industry sectors, where companies often rely on temporary contracts of a bigger workforce. The robot can be stationed to any workplace and perform repetitive tasks, being a useful tool for dealing with these fluctuations. Also, for older machines that lack any communication with the virtual domain, the robot can read their interface and actuate on buttons and levers accordingly, increasing the connectivity of older machines without needing to replace them. However, care must be taken in choosing which machines the robot should interact with, avoiding hazardous situation. In case of any emergency or problem, the robot can also be commanded, directly or remotely, to press any emergency stop button on any of the machines, possibly diminishing the consequences of work accidents.

1.3 Human-Robot Interaction

Human-robot interaction can be described as the information exchange between human and machine [12]. Although human-robot collaboration allows to relieve operators of exhausting works, an effective collaboration requires a straightforward interaction to foster the use of robot assistants [13].

Intuitive communication with the robot is key in allowing a good interaction with the robot. In [14] both visual and audio commands are used to program a robot for a pick and place task. The user can point and gesture to the robot and issue simple voice commands in order to guide it and train it in the desired operation.

Considering the emotional response of humans when interacting with the robot, there are proven results which verify a more positive attitude towards interacting with more human-like robots [15]. However, it should also be noted that if a robot is excessively human-like, due to the uncanny valley phenomenon the response becomes a lot more negative [16].

Safety is one of the main concerns when regarding interaction with robots. This safety is relevant in two different ways. The actual safety mechanisms of the robot and how it avoids creating any hazardous situation or accident, and the perceived safety of the human collaborating in the robot. It is mandatory for the robot to be safe, but it is also important to allow the operator to feel safe around it [17]. The International Standards Organization (ISO) published several standards related to risks, hazards and safety requirements for human-robot cooperation in industrial environments, which should be verified [18,19].

The robot's input information must be able to always determine when the robot is close to a human. The conjugation of the designed robot's vision sensor, ultrasound sensor information and a LIDAR sensor must guarantee verification of this condition. Power and Force Limiting (PFL) regards collaboration where psychical interaction between a robot and an operator occurs [20]. The risk reduction is related to a suitable robot design, suited limit criteria for contact events and design and control choices to respect said criteria, reducing the kinetic energy in an eventual impact during human interaction. In [20] a formal verification approach to safety in human-robot collaboration is proposed to assessing the possible risks and studying the safety of the collaborative environment.

Design choices during the robot's project must be made to ensure the robots inputs and outputs are robust and reliable enough to ensure constant safety in human-robot interaction.

1.4 Current state of the project

At the time of writing this paper, prototypes for the locomotion system, suspension systems and the lower limbs of the robot have been built and analysed, validating the theoretical approach made for both these modules. The used methodology is later described in this paper. Work on speech recognition and object detection is also under way with some preliminary results already obtained on object detection. The project of the arms and main body of the robot is now beginning, along with the development of the kinematic control and decision-making modules.

2. STATE OF THE ART

Redundant manipulators have seen great use in industrial applications performing repetitive tasks in fixed workstations. However, interest in mobile manipulators is growing due to their higher adaptability and flexibility at work.

Robotic competitions, such as DARPA's Robotics Challenge [21] and RoboCup [22] incentivise the development of robotics and are an important way of setting benchmarks. Although for different applications, these competitions both require usage of mobile manipulation.

Regarding the DARPA's Robotics Challenge, the tasks performed where related to emergency response and dealing with hazardous situations. Object interaction with handles and doors was like what could be found in an industrial environment. Remote controlling the robots was a possibility, but most teams searched for use of an autonomous solution with remote controlled decision making [21]. Out of 25 mobile manipulators, 21 chose to use humanoid designs. The top three robots of the competition where able to complete all proposed tasks which included opening and closing door, valves and using tools. The first place, DRC-Hubo from Korea's Advanced Institute of Science and Technology [23], is an 80 kg humanoid robot with legged locomotion, with two arms, each with a claw like hand with two degrees of freedom. The second-place team, IHMC Robotics, adapted Boston Dynamics' Atlas [24]. This robot also presented a 175 kg humanoid design with legged locomotion, with two arms for object interactions. The third place robot, Tartan Rescue's CHIMP [25] was one of the robot which deviated from a humanoid design. As it is named, the robot was designed to look like a chimpanzee. It weighs 201 kg and possesses two arms with 7 degrees of freedom each for object interaction. This robot presents a hybrid locomotion. It is a legged robot, but its "feet" are tracked for allowing a tracked locomotion as well.

RoboCup@Home Open Platform requires the design of robots for working in a domestic environment. Robots in this competition are required to comprehend human speech, follow orders, interact with objects, avoid obstacles and following a human. All the tasks should be performed autonomously with a focus on human-interactions. Although the robots are developed for working at home, many features and technologies share a common ground with robots designed for industrial environments. Analysing results from the 2018 competition, the winning team, @Homer from the University of Koblenz [26] used two robots Lisa and TIAGo from PAL-Robotics. TIAGo [26] has a differential-driven wheeled locomotion, a torso with a prismatic joint with a 35 cm course and a single 7 Degrees of Freedom arm mounted on the torso. Lisa [26] also has a differential-driven wheeled locomotion with a single 6 Degrees of Freedom arm mounted on the torso for object manipulation. The second-placed robot Justina from team PUMA [27] has a human-like design, with two arms for object manipulation mounted on a torso with a worm screw mechanism for prismatic movement, and four omnidirectional wheels for locomotion. The third placed robot was Tech United Eindhoven's AMIGO [28]. This robot has a human-like design with a four-wheeled omnidirectional locomotion system, a torso with 1 vertical degree of freedom and two Philips Experimental Robotic Arms with seven degrees of freedom each for object manipulation.

Usage of artificial intelligence for decision making has been a problem often tackled in programming. For analysing and testing the solutions, board games and video games have been often used in reinforcement learning since they offer a controlled environment with a set number of rules and are often related with direct metrics for performance evaluation (points). One of the greatest breakthroughs of using neural networks for decision making was made in 2016, where Google DeepMind's AlphaGo was able to autonomously defeat one of the world's best players [29]. This game's game-tree complexity is 10^{360} possible moves, quite superior to the game-tree complexity of chess of 10^{123} possible moves [30]. Google's DeepMind is now tackling the videogame Starcraft II with AlphaStar. The real-time decision making of this game is of a superior complexity, offering an infinite number os possible choices at any given time [31]. However, the developed AI was already able to defeat a professional player, however with some restrains regarding the possible match settings. These proven results highlight the possibilities of reinforcement learning for decision making problems, strategies that can be transposed to the problems tackled in the robot's brain, the decision-making modulus.

In voice detection and human interaction, Japan has already installed, for public usage, an interactive artificial intelligence named Sakura AI. This artificial intelligence is already capable of speech detection and production in four different languages (Japanese, English, Korean and Chinese). Another popular usage of speech recognition are intelligent virtual assistants such as Amazon Alexa, Amazon Echo or Apple's Siri [32]. Apple's Siri also uses Deep Learning for optimization of text-to-speech production for a more natural and expressive voice [33].

Regarding commercial mobile manipulators for Human-Interaction or industrial applications, PAL Robotics is currently developing ARI, a robot still on a conceptual stage designed for service robotics and artificial intelligence with focus on Human-Robot interaction. Robotnik's RB-KAIROS [34] is designed for autonomous mobile manipulation in an industrial environment. It consists of a single manipulator arm, which can integrate a range of end-effectors, such as cameras and grippers, mounted on a 4 mecanum wheeled locomotion system.

Autonomous mobile manipulation is seeing increased usage in the agriculture industry, such as HV-100 from Harvest Automation [35]. Such robots often possess autonomous locomotion and object interaction, with a set of sensors for monitoring the state of plants, and actuators for watering or harvesting plants.

An approach to mobile manipulation in industrial environment has been made by coupling two robots with proven positive results in the industrial sector, an available redundant manipulator for object interaction and a mobile base to give it locomotion. An example of this is Clearpath Robotics which developed Ridgeback [36], an indoor omnidirectional platform made for easy integration of a variety of manipulators. Rethink Robotics Baxter [37] can be easily coupled with this base, acquiring a mobile manipulator. It should be noted that many redundant manipulators are only made for preprogramed movement, not having the required range of sensors for autonomous manipulation.

Aalborg University is developing Little Helper [38]. The robot consists of a mobile base with a mounted 6-DOF redundant manipulator. The robot's end-effector has the possibility of tool integration and tool change. After training and teaching the robot in its work environment, it can perform tasks with control via machine communication routines or via predefined work cycles.

3. METHODOLOGY

The methodology used for the robot's already prototyped mechanical subsystems (suspension system and lower limbs of the robot) will now be described. [39]

3.1 Suspension System

The suspension system will be directly connected to the locomotion system, requiring a short description of the robot's locomotion. This system is responsible for movement of the robot around the workspace. The robot is designed for indoors industrial work, being wheels the advised choice of locomotion.

Four 203 mm double aluminium omni wheels with bearing rollers, with a load capacity of 50 kg each, were used. Each wheel is coupled with an EMG49 24 V DC motor. These motors have a rated torque of 1.6 Nm and a rated speed of 122 rpm. A 3D model of the assembly of the motor, the omni-directional wheel and the components for coupling with the structure (or the suspension arm), is shown in Figure 3.

When three omni-directional wheels are used, continuous contact of them all with the floor plane is guaranteed. However, when a fourth one is introduced, it is possible for one to lose contact with the floor, resulting in an unpredictable and hard to control behaviour. A compact suspension system was developed to avoid this problem, as well as mitigate the effect any irregularity on the floor will have on the robot.

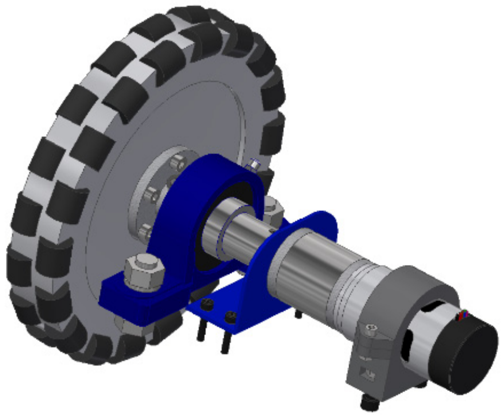

Figure 3. 3D model of the assembly of the omnidirectional wheel and the DC motor

Since each wheel will have its own associated motor and independent movement, the chosen suspension was an independent suspension system, where each of the wheel will have its own relative movement to the base [40]. Three main suspension types were considered [41]:

- MacPherson Suspension: The wheel has a rotational movement in relation to the structure. That movement is dampened by a spring connected to the structure. Figure 4 A.
- Double Wishbone Suspension: This suspension consists of a four-bar mechanism which allows some control of the angular orientation of the wheel. Movement of the mechanism is dampened by a spring connected to the structure. Figure 4 B.
- Multilink Suspension: Any independent suspension with three or more arms is considered a multilink suspension. These are the most complex kind of suspensions, but with a higher control and customization options.

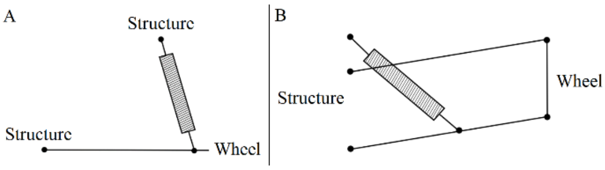

Figure 4. Schematic representation of a MacPherson suspension (A) and a Double Wishbone suspension (B)

Due to the reduced size of the base, a MacPherson suspension was used, since it is the simplest and most compact of solutions. Figure 5 shows the designed suspension and its main components.

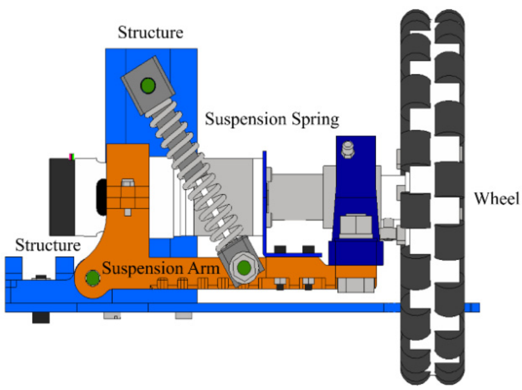

Figure 5. Schematic representation of the designed suspension system

In a MacPherson suspension, compression or extension of the spring will always result in a variation of the camber angle α of the wheels (Figure 6). Omnidirectional wheels are designed to work with a camber angle of 0º, so it's important to guarantee this angle is verified for normal work conditions with no solicitations.

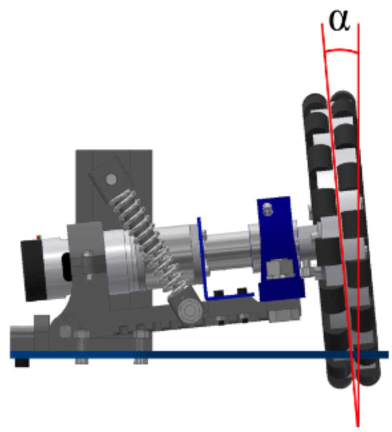

Figure 6. Representation of a negative camber angle on the robot's suspension system

Reduced size also comes as a limitation for the suspension's travel distance due to interference between components. The goal is maximization of this distance to increase how much the spring can compress, dissipating impact energy without transmitting it directly to the structure.

Three main interference types were analysed:

- Interference between the wheel and the base's lower plate for both positive and negative camber angles
- Interference between the suspension's arm and the base's lower plate for positive camber angles
- Interference between two of the DC motors for negative camber angles

Mathematical equations were established for all interference types resorting to trigonometry. All equations were solved in relation to the camber angle α, establishing how each of the suspension's dimensional parameters (arm length, position of the spring, wheel position, position of rotational joints, etc.) affected this angle's limits. This allowed an optimization of the geometry to maximize the achievable range of motion. The maximization of the modulus of the negative camber was prioritized for it corresponds to compression of the spring, where energy is being dissipated.

The choice of spring required a balance between its geometry and the forces applied on it. When the system's forces are balanced, the camber angle must be 0º. A free body diagram of the suspension arm is represented in Figure 7.

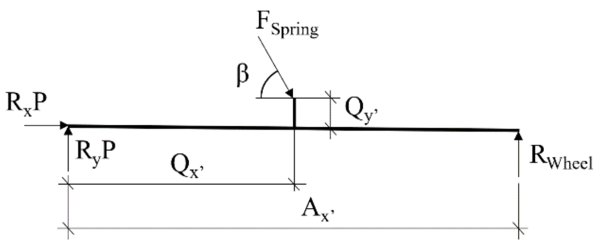

Figure 7. Free body diagram of the suspension arm

The spring's force can be calculated with (1).

$$F_{Spring} = \frac{A_{x'} R_{Wheel}}{\left[Q_x \sin(\beta) + Q_y \cos(\beta)\right]} \quad (1)$$

where F_{Spring} is the spring's force, $A_{x'}$ the suspension arm's length, R_{Wheel} the reaction force of the wheel, directly proportional to the robot's weight, $Q_{x'}$ and $Q_{y'}$ determine the position of the rotational joint between the arm and the suspension's spring and β is the angle between the suspension's arm and the spring. The chosen spring, when compressed to the position corresponding to the system's equilibrium, must apply a force equal to F_{Spring}. A database of springs was compiled for an automatic choice of spring by defining geometric characteristics for the suspension and limiting parameters for spring choice, such as minimum and maximum size.

The forces applied on the structure by the suspension arm are R_xP and R_yP. To reduce load on the structure, minimization of these forces is advised. Analysing the free body diagram of Figure 7, after simplification, those forces can be expressed as:

$$R_x P = \frac{A_{x'}}{Q_{x'}} \times \frac{R_{Wheel}}{\tan(\beta)} \quad (2)$$

and,

$$R_y P = R_{Wheel}\left(\frac{A_{x'}}{Q_{x'}} - 1\right) \quad (3)$$

By analysing (2) and (3), it is possible to determine that the optimal geometry for minimization of the forces will be approaching β to 90º as much as possible (to minimise it's tangent) and positioning the rotational joint of the spring in relation to the suspension's arm as close to the wheel as possible, minimizing the division between $A_{x'}$ and $Q_{x'}$. R_{Wheel} cannot be changed since it has a direct relation to the robot's weight.

An attempt to achieve this optimal position with smaller loads was made. However, the perfect position could not be reached due to the previously set constrains of interference between components. An optimization was made which aimed to find the best compromise between lowering the force, guaranteeing a correct range of motion and choosing a geometry with an adequate corresponding spring for assembly.

To achieve this optimization, all equations and geometrical parameters were defined in a mathematical worksheet and an iterative analysis was made. This analysis allowed a comprehension of how each of the geometric parameters would affect the system's overall performance. The considered inputs where the robot's weight, the geometric parameters and the chosen spring. The outputs taken were the suspension's range of motion, minimum and maximum force the spring could apply and applied forces on the arm, spring and structure on regular working condition.

The chosen weight considered was only an estimation (50 kg). A future optimization of the suspension's geometry is required to face the difference to the robot's real weight. Since most of the suspension system's components where made resorting to additive manufacturing technologies of PLA, such geometry changes will be easily made, requiring only small adjustments on the 3D model and reprinting of components.

To validate the applied principles and begin work on programming the control of the robot's locomotion, a prototype was built (Figure 8). The prototype's weight is 22 kg. Rotational joints were made using 8 mm diameter steel rods.

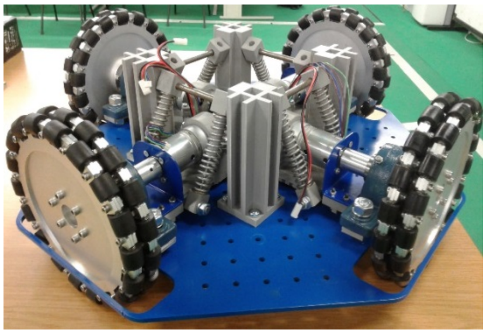

Figure 8. Built prototype of the robot's locomotion and suspension systems

Inspection of the prototype allowed verification of the worksheet's outputs. The range of motion of the prototype corresponded to the one determined. The required weight to achieve a balanced position was also verified. The structural integrity of the suspension system was confirmed, being able to support loads greater to those that the robot will be subject to under normal work conditions.

3.2 Lower Limbs of the Robot

To design the lower limbs of the robot, the following main requirements were taken into consideration:

- Structural integrity to support the robot's weight
- Anthropomorphic look
- Self-locking actuation to reduce energy consumption
- Allowing the robot to squat, increasing its workspace and making it able to interact with objects on the floor

The mechanism designed for the lower limbs is represented on Figure 9. It consists of two parallelogram four-bar mechanisms (bars 1; 2 ;3 ;4 corresponding to the tibia and bars 4; 5; 6; 7 corresponding to the femur) and an inverse slider-crank mechanism (bars 7; 11; 12; 13 corresponding to the body).

A linear actuator was chosen to actuate the slider crank mechanism in order to help attain a self-locking mechanism. Since individual control of the position of each of the sub mechanisms is not required, the robot only needs to be able to squat, sets made by bars (8; 9; 10) and bars (14; 15; 16) transmit angular movement from each of the sub mechanisms to the other, reducing the number of degrees of freedom from three to one.

Actuation on the inverse slider-crank mechanism results in a controlled rotation of bar 11, which is transferred to bar 5, parallel to bar 6 whose angular movement is transferred to bar 3.

Grübler's criteria for a planar mechanism with n bodies, one of which is fixed (4), was applied, where j_1 is the number of primary joints, j_2 the number of secondary joints and DOF the resulting number of degrees of freedom. Considering the mechanism has 16 bodies, 22 primary joints and no secondary joints, the resulting number of degrees of freedom is only one as desired.

$$DOF = 3(n-1) - 2j_1 - j_2 \tag{4}$$

The kinematic analysis of the lower limbs' mechanism can be consulted in [42].

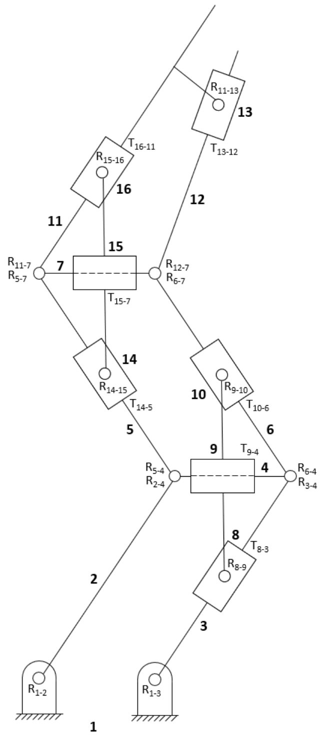

Figure 9. Mechanism of the robot's lower limbs

For ease of prototype construction, square steel tube was the main structural component used, with laser cut sheet metal aiding in joining the tubes. For rigid connections, threaded components were used for an easy assembly and disassembly of the prototype. For rotational joints, steel rods (H8) were inserted into holes drilled into the steel tubes (f8) [43]. For prismatic joints, linear bearings were used to slide along steel rods. The actuator chosen was an electric linear cylinder. For future mass production, square steel tube will likely be replaced by a redesign using mostly bent and laser cut steel sheet. The current design of the lower limbs is represented in Figure 10.

The main limitation for minimum (θ_{min}) and maximum (θ_{max}) angles the lower limbs could reach is interference between components inside the hip and knee. The attained range of motion after optimization is between 30º and 85º.

The lower limbs will house the components with the highest loads and stresses of the robot, requiring an adequate dimensioning to guarantee structural integrity. A more in-depth analysis of the structural dimensioning can be consulted in [39,42].

The static stability of the robot was then analysed. Static stability is associated with the position of the centre of mass. A representation of the robot's centre of mass, relevant geometric parameters and forces is represented in Figure 11.

Figure 10. 3D model of the prototype's lower limbs

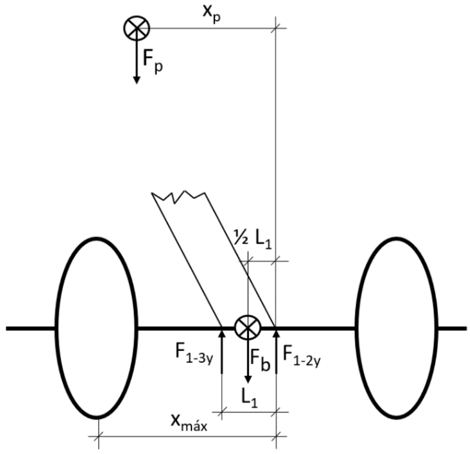

Figure 11. Representation of the robot's centre of mass position

A simulation previously made in *Working Model 4D* allowed to determine the forces in the lower limbs. This allows knowledge of $F_{1\text{-}2y}$ and $F_{1\text{-}3y}$ along the range of motion, which means that the upper body's weight F_p can be determined. The position of the upper body's centre of mass x_p was calculated through analysis of the balance of forces and moments. F_b is the weight of the robot's base and x_{max} the limit established for the global centre of masses' position related with the point of contact of the wheels with the floor. The condition which should be verified to guarantee the static stability of the robot is shown in (5).

$$\frac{F_p \times x_p + F_b \times \frac{L_1}{2}}{F_p + F_b} < x_{\max} \tag{5}$$

To validate all theoretical approaches to the mechanism of the robot's lower limbs, a prototype was built, shown in Figure 12.

Only one of the legs was built for testing. The chosen actuator had a maximum load of 6000 N and a 100 mm stroke length. The operations used to build the structure were turning, FDM 3D printing, cutting and drilling. The square steel tubes were mainly hollow with a 16x16x1 mm cross section, except for the tubes used on the hip, which were massive due to higher installed stress. The rods used for rotational joints had 8 mm diameter and for prismatic joints 12 mm diameter.

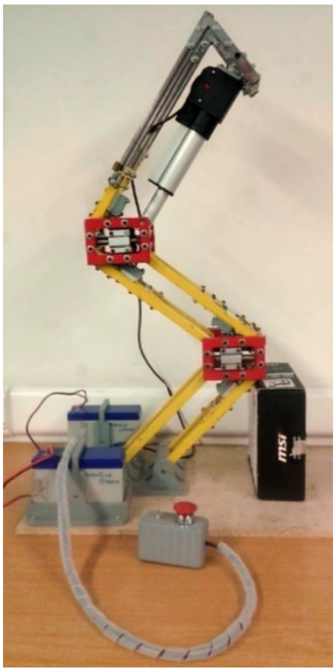

Figure 12. Prototype of the mobile manipulator's lower limbs

A controller with a basic electronic circuit was built to test the prototype. The cylinder will be powered by 12 V direct current. To change the movement direction of the actuator all that is needed is a polarity inversion. The cylinder already possesses internal end of stroke sensors which automatically stop power supply when a limit position is reached. The controller, besides possessing a switch that can reverse the polarity, also includes an emergency stop button to avoid potential damage to the prototype.

Analysis of the prototype allowed to verify the correct motion with no interference between components and correct behaviour of the kinematic chain. Due to the long kinematic chain, it's important to minimize the gaps on the joints. The structural integrity was also tested, validating the structural dimensioning.

4. RESULTS

Results obtained from the methodology applied for both the suspension system and the lower limbs of the robot will now be presented.

4.1 Suspension System

The suspension system allowed a correct operation of the locomotion system, which previously had the main flaw of one of the wheels losing all traction due to loss of contact with the floor.

The maximum camber angle α_{max} is 1.9º which corresponds to a spring extension of 3.0 mm. The minimum camber angle α_{min} is -5.5º which corresponds to a maximum compression of the spring of 9.1 mm.

Characteristics of the chosen spring are shown in Table 1 [44]. It should be taken into consideration that two springs were installed in parallel in each of the independent suspension systems.

Table 1. Characteristics of the chosen spring for the suspension system

Characteristic	Value
Free length of spring L_0	110.0 mm
Wire diameter d	3.0 mm
Mean coil diameter D_m	17.0 mm
Number of active coils N_a	12.75
Shear modulus G	77.2 MPa
Spring rate k	13.4 kN/m
Spring end type	Plain end, gound, left hand

The resulting forces applied on the suspension's arm for equilibrium conditions for a robot weight of 50 kg are shown in Table 2.

Table 2. Forces applied on the suspension's arm for equilibrium conditions

Force	Intensity
Wheel reaction R_{Wheel}	122.6 N
Spring force F_{Spring}	241.2 N
Reaction on the robot's structure (x axis) R_xP	127.1 N
Reaction on the robot's structure (y axis) R_yP	82.4 N

4.2 Lower Limbs of the Robot

Besides validation of the geometrical characteristics and calculation of the weight of both lower limbs (15 kg), the main results obtained from the lower limbs were related to structural dimensioning.

Inspection of actuator forces along the length of movement shows a constant increase of force as the displacement of the actuator increases (Figure 13). Due to the predictable variation of forces along the movement, the inclusion of a compression spring parallel to the actuator in order to reduce its load can be considered. The required behaviour from the spring can be attained from a linear regression of the force-displacement graph of the actuator.

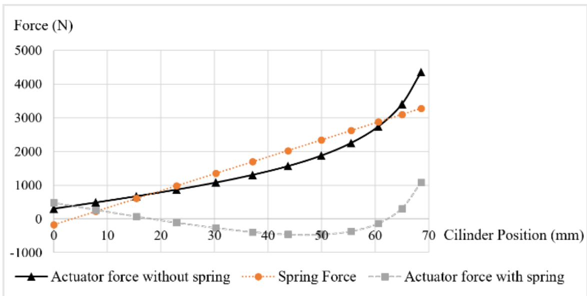

Figure 13. Forces on the actuator of the lower limbs

Results on Figure 13 show the force made by two compression springs with a spring rate of 25.1 kN/m each installed parallel to the linear actuator and whose rest position correspond to a 3.4 mm cylinder position. In this case, the maximum strength required from the actuator reduces from 4350 N to 1080 N. This also has the added benefit of permitting a distribution of load on the structure, not having it all concentrated on the cylinder's rotational joints.

5. WORK IN PROGRESS

Future work on the robot will be focused on completion of a fully functional prototype.

The locomotion system and suspension systems are finished, only requiring a small redesign of the support structure for a better integration of the lower limbs of the robot.

The lower limbs are being optimized and redesigned for simplicity of mass production and an increase in reliability. Such redesign will possibly include springs in parallel with the linear actuator to reduce its work-load. Ball bearings will be installed in rotational joints to decrease their friction and guarantee a tighter fit. Future work on the lower limbs should also include a stability analysis which includes dynamic effects.

The main body of the robot and the upper limbs (redundant manipulator), as well as their end-effector (hand-like robotic gripper) are being studied and projected. Work on the upper body is advancing toget-her with the development of neural networks for the robot's kinematic control, being the choice of design, sensors and actuators the basis for the inputs and outputs of the neural network.

For a first stage of image processing, Convolutional Neural Networks were used. These networks allow comprehension of patterns, edges and formats to classify certain objects. Image acquisition from the camera was made using the *OpenCV* library, and the neural network was implemented using the *Tensorflow* library. The result was real time recognition and classification of objects and determination of their coordinates on a 2D level. Further work is required for depth recognition [45].

Figure 14 shows the results of the neural network after training for detection of various bottles in any position.

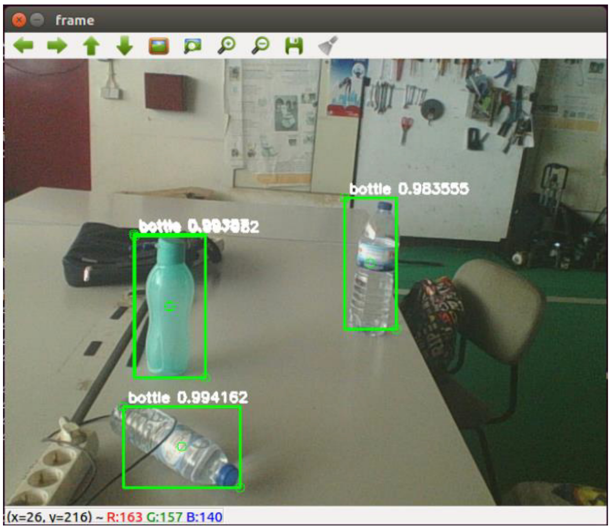

Figure 14. Detection of water bottles and their position using a laptop camera after training of the neural network. Image taken from: [45]

Results for the average precision of the object detection are shown in Figure 15 where the average validation precision was above 80%.

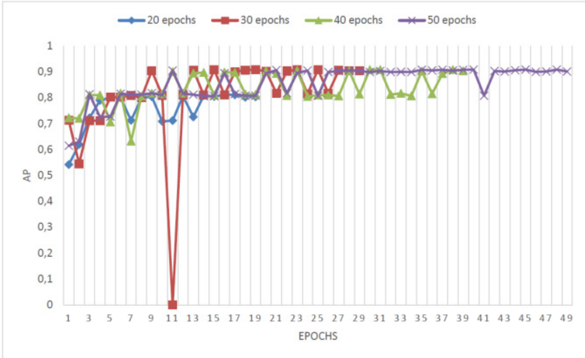

Figure 15. Average precision of the neural network for different number of epochs. Image taken from: [45]

The usage of neural networks for pathfinding has also begun by studying simpler cases. Q-Learning was proposed as a Reinforcement Learning solution for obstacle avoidance. This first solution was implemented and tested in a *Bot'n Roll One A* robot which autono-mously found and optimized its way around a track laid out in three labyrinths. Although this is a simpler robot, the problem tackled can be scalable for the mobile manipulator. Implementation of the neural network and optimization was made in a simulation environment which integrated both physical aspects of the robot and as well as its operating system [46]. This robot had a smaller amount of input information to work with than the developed prototype, where a LIDAR is used to map the surrounding environment and ultrasonic sensors will be used to detect any obstacle close to the base in a 3 meter radius to guarantee avoidance of any collision.

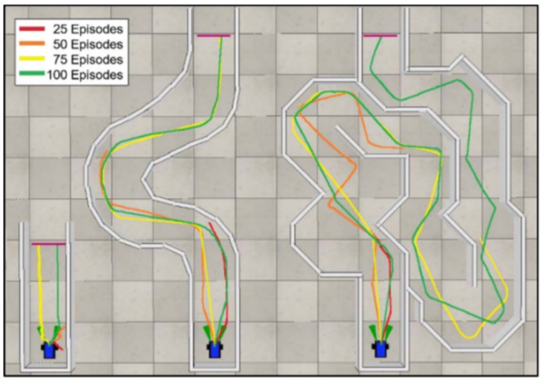

Figure 16. Trajectory of a Bot'n Roll One A robot autonomously solving a maze using Q-Learning. Image taken from: [46]

Work will begin on the main neural network responsible for the robot's "brain", related to processing information and decision making. It is expected a discretization and hierarchisation of the possible decisions the robot can take and build a neural network to optimize such decision-making process. A preliminary study of voice recognition has already begun, but a more in-depth study is starting with the goal of attaining a clear and reliable interpretation of simple commands and orders.

6. CONCLUSION

Using applied mechanical engineering methodologies, a functioning prototype of two of the robot's mechanical subsystems was achieved. The principles described were used for a specific solution, however they can be generalized and used for parametric analysis and optimization of similar solutions in different robots.

Usage of this methodology of optimization though a worksheet allowed for a quick and versatile analysis of each iteration of the developed solution, does not only contribute to the current version of the prototype, but establishing a solid foundation for any future work.

The construction of a prototype allowed a validation of the applied methodology, as well as provision of the insight into the improvements for future works, such as using bearings to lower rotational joint friction.

The solutions presented proved for both the suspension and the lower limbs of the robot to be advantageous for the following reasons:

The suspension system allowed a simple, compact, cheap and easy to assemble solution for the previously found locomotion problems. This increased the reliability of the locomotion system and made its control simpler. The robustness of this compact solution allows its usage for robots with weights of up to 100 kg.

Studies on different human-robot interaction, such as elderly care, have shown a preference for interaction with human-like robots [3]. The proposed design of the lower limbs allows the robot's squatting motion to mimic human movement, enhancing the attractiveness of the robot without increasing the complexity of the robot control system, the number of required actuators for this motion being only one.

With two mechanical subsystems studied, work on other mechanical subsystems of the robot has already begun. The next stages of the project are already defined with the aim of developing a fully operational robot that can become a valuable resource in industry 4.0.

ACKNOWLEDGMENT

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РАЗВОЈ АНТРОПОМОРФНОГ МОБИЛНОГ МАНИПУЛАТОРА СА ИНТЕРАКЦИЈОМ ЧОВЕКА, МАШИНА И ЖИВОТНЕ СРЕДИНЕ

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Ф. А. Рибеиро, К. Монтеиро, Ж. Лопеш

Антропоморфни мобилни робот за манипулацију („*CHARMIE*") развија се у Лабораторији за аутоматизацију и роботику Универзитета Мињо (ЛАР). Робот прикупља сензорске информације и обрађује их коришћењем неуронских мрежа, делујући у реалном времену. Две руке робота дозвољавају интеракцију објекта и машине. Његова антропоморфна структура је повољна јер су машине пројектоване и оптимизоване за људску интеракцију. Излаз звука омогућава да се информације преносе радницима и дају повратне информације. Усаглашавање ових карактеристика са комуникацијом са базом података или удаљеним оператором доводи до успостављања моста између физичког окружења и виртуелног домена. Циљ је повећање протока информација и приступачности. Овај рад приказује тренутно стање пројекта, предвиђене карактеристике и начин на који може допринети развоју Индустрије 4.0. Фокус је дат на већ завршен рад, детаљно описујући методологију која се користи за два подсистема робота: систем кретања; и доњи чланци робота.