MATEC Web of Conferences **388**, 04002 (2023)
2023 RAPDASA-RobMech-PRASA-AMI Conference
https://doi.org/10.1051/matecconf/202338804002

ARGUS: a pole climbing surveillance robot

W de Ronde[1], *P* Bosscha[2], *S* Marais[3], *A* Pretorius[4]

[1] Centre for Robotics and Future Production, CSIR, wderonde@csir.co.za
[2] Centre for Robotics and Future Production, CSIR, pbosscha@csir.co.za
[3] Centre for Robotics and Future Production, CSIR, smarais@csir.co.za
[4] Department of Mechanical Engineering, UCT, arnold.pretorius@uct.ac.za

Abstract. Due to the high prevalence and unpredictability of violent protest action in South Africa, a need has arisen for rapidly deployable surveillance. This paper proposes an Automated Robotic Guardian for Urban Surveillance (ARGUS) platform, a wheeled, pole climbing robot as a potential solution. The platform is designed to attach to and traverse up existing cylindrically shaped infrastructure, such as light posts, enabling easy deployment in urban environments. The robot is intended for various surveillance needs, such as public safety at events, and periods of unrest or protest action. Following a detailed concept design stage, simulated results are presented for the proposed robot. This includes comprehensive CAD modelling, static force and torque calculations of the pole climbing robot, and finite element analysis of the component stresses while positioned on the pole. The robotic platform is currently in production and future work will include experimental validation of the simulated system.

1 Introduction and Background

South Africa has a high occurrence of public unrest due to multiple factors, ranging from lack of service delivery to racial and political issues. Legally organised protests are required to give notice of such an action to the responsible officer concerned [1]. The police have a responsibility to keep protesters, bystanders, and infrastructure safe. Not all public protests turn violent, but irrespective of this, the monitoring of a protest is still advantageous.

The need for such a platform has become glaringly clear during major protests and incidents in recent years, such as the student protests in 2015, under the slogan '#FeesMustFall', and the July insurrection in 2021, which impacted large parts of KwaZulu-Natal and part of Gauteng [2]. The property damage of the Fees Must Fall protest is estimated to be in the order of R600 million, and allegations of police brutality were widespread [3]. Protests are commonplace throughout the country, with most instances taking place in highly populated, urbanised areas, as can be seen in **Fig. 1**. In 2020 a total of 1378 public protests were recorded [4].

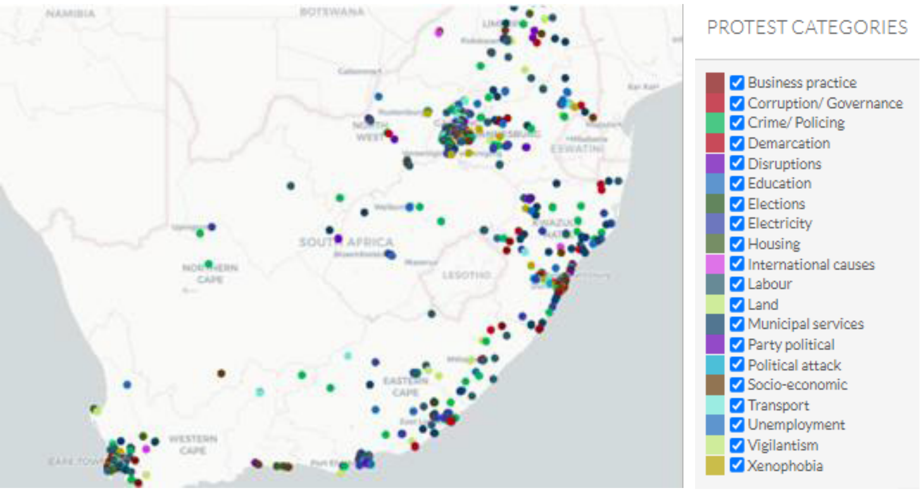

Fig. 1: Public protest and violence map for South Africa in 2020, courtesy of [4], used under Creative Commons 4.0 International

The work in this paper describes a rapidly deployable robotic system, consisting of a motorised pole climbing mechanism and a video surveillance solution payload. The proposed system has applications in entertainment events and law enforcement needs, where existing poles can be used as support to elevate the surveillance system. A diagram of the proposed system can be seen in **Fig. 2**.

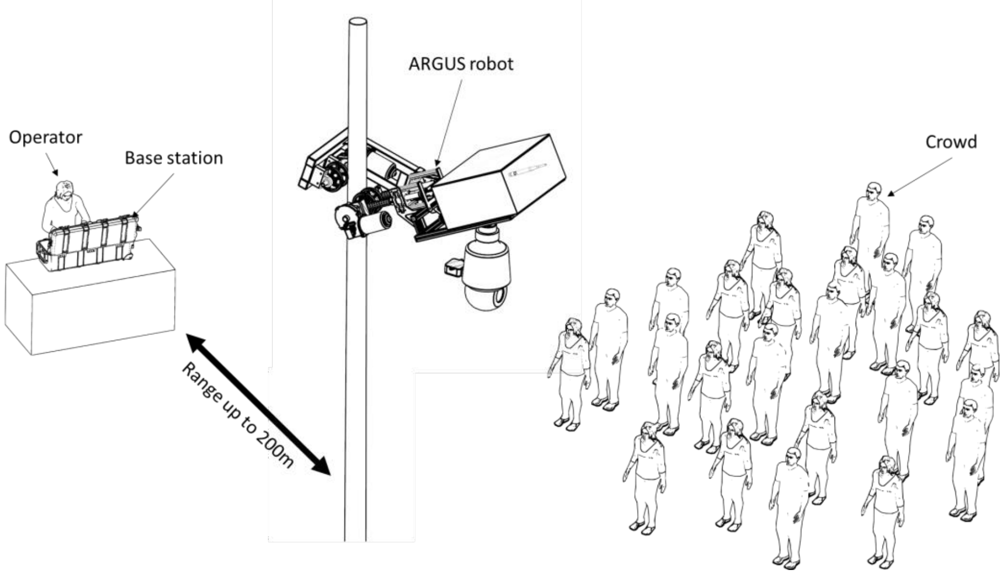

Fig. 2: Diagram of ARGUS system, depicting the operator, robot and crowd

Extensive research has been conducted over the past few decades on pole climbing robots, with the focus being predominantly on inspection applications of the pole itself. Various solutions have been proposed for pole climbing mechanisms, and a taxonomy tree of these can be found in **Fig. 3**. The classification of wheeled robots is divided into wheels relying on friction for traction [5-10] and wheels that use magnets for traction [11]. Nature has created a multitude of creatures that can climb using different mechanisms. Researchers, implementing biomimicry, have been inspired to build robotic platforms utilising these mechanisms. The mechanisms are divided into robots with grippers and segmented joints [12-14], soft robotics [15] and quadrupedal [16].

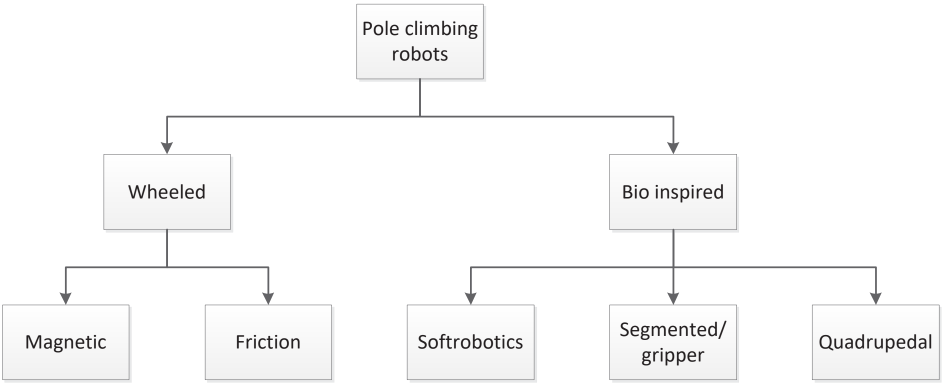

Fig. 3: Pole climbing robot taxonomy tree

An example of a wheeled robot is the *University of Tehran Pole Climbing Robot* (UT-PCR). The first iteration of the robot, the UT-PCR1, is a wheeled base, nonholonomic mobile robot [5,6]. The robot clamps onto the pole by means of six wheels, which are divided into three sets.

These wheelsets are distributed around the pole in 120-degree increments to ensure stability, and each set consists of one passive wheel at the top and one active wheel at the bottom, where both wheels are spring-loaded onto the circumference of the pole. The spring-loaded wheels enable the robot to passively accommodate different pole diameters and change the diameter of the pole during ascent and descent. To attach the robot to a pole, the triangular body of the system is opened on one side. The robot is then placed onto the pole, and the side is closed again [6].

An example of a bio-inspired robot is *Climbot*, a bipedal climbing robot inspired by the climbing motion of the inchworm, for high-rise work on poles, trusses, or trees. The main aim of the system was to improve the mobility of the climbing system, compared to other existing systems at the time, and to have the ability to manipulate. The system consists of five single degree-of-freedom (DoF) modular joints that are connected in series. Each end of the system has a gripper attached to it. This enables the system to use the same mechanism for climbing and manipulation, eliminating the need to mount a secondary manipulator on the Climbot [12].

This paper describes the development of a surveillance robot, the ARGUS platform, which is designed for rapid deployment in urban environments. This contribution involves designing a wheeled robot capable of climbing cylindrical structures, such as light posts, which could be a significant advancement in surveillance technology. In this paper, the Methodology will elaborate on the process that was followed to arrive at a detailed design.

2 Methodology

A user needs analysis was completed to establish what the user wants to achieve with the project. These needs were then converted to a User Requirement Specification (URS) document to guide the design and development of the robotic system. Inputs into the URS came from existing pole climbing robot research and products as well as from specifications on South African pole infrastructure [17,18]. Several concept designs were created, by means of 2D sketches, which were evaluated against the URS, and a best fit selection was made. A detailed design was implemented on the chosen concept, using Computer Aided Design (CAD) with calculations performed using MITCalc [19] and Engineering Equation Solver (EES) [20], followed by simulations in Simcenter [21] to prove correct functionality, ensuring that the sub-systems and components will function correctly under the calculated loads and forces.

All requirements and design documentation, Computer Aided Design (CAD) files and documentation pack was managed and coordinated through the Product Lifecycle Management (PLM) tool known as Siemens Teamcenter [22], which allows centralised version-controlled project information. A diagram of the modified V model approach that was followed can be seen in **Fig. 4**.

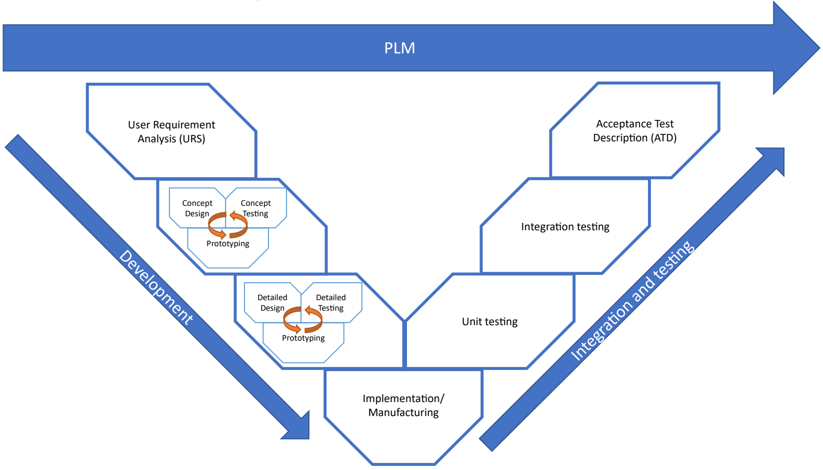

Fig. 4: Modified system engineering V-model

2.1 Requirements

The user needs and key user requirements can be seen below.

User needs analysis

- Obtain situational awareness in certain scenarios.
- Temporary, rapidly deployed surveillance solution.
- Deployable and operable by a single operator.
- Deployed solution to be self-powered.
- Elevated position from which to obtain situational awareness, therefore using existing pole infrastructure.
- Remote video feed transferred to a safe location.

Key User Requirements Specification

- The system shall be able to attach to cylindrical poles of diameter between 65mm and 240mm.
- The system shall be able to handle a change in diameter of 40%, after being attached to the pole, up to a maximum of 100mm change and with a minimum of 50mm actual pole diameter.

- Once ascended onto the pole, the system shall be able to keep itself in position using little to no power.
- The system shall be able to run surveillance equipment for at least 4 hours.
- The system shall have bidirectional wireless connectivity.
- The wireless connectivity should have sufficient bandwidth to stream 1080p video and control the robot.
- The robotic system should not weigh more than 20kg, to facilitate the deployment of the system by one person.

These requirements informed the development of the robotic platform discussed in the following section.

3 Development Stages and Simulation Results

The robotic platform was taken through multiple stages in its development. Concept designs were generated to evaluate different approaches to meet the client’s needs. A prototype of the chosen concept was then constructed to test some of the aspects and better understand the proposed design. The insights gained from this process were then implemented in a detailed design of the robotic platform that is presented in this paper.

3.1 Concept design

Four distinct concept designs were generated, each implementing unique and innovative methods. These concepts were evaluated using a comprehensive set of criteria, including adherence to the specified requirements, as well as the level of complexity and ease of manufacturing. By carefully considering each concept's strengths and weaknesses in these areas, the design with the most potential for success was selected. This approach enabled us to make an informed and confident decision on which concept to move forward with for further development and refinement. These concepts will be described below.

The first concept employs a similar mechanism to that of a parallel gripper, which consists of a linear actuator that moves two sides, each comprising of two arms spring-loaded to each other with wheels at the ends, to clamp onto a pole and is shown in **Fig. 5**. This design, utilising the linear actuator, allows for adjustment to accommodate different base pole diameters, while the spring-loaded arms enable the system to adapt to changes in diameter over the length of the pole and navigate small obstacles. The actuator could also be used for active adjustment while traversing the pole. The linear actuator and springs generate a reactive normal force from the pole that gives the robot traction, the centre of mass located toward one of the sides of the machine will also cause a moment that increases the amount of traction possible. To enable vertical movement, at least one of the wheels will be actively driven to traverse up and down the pole.

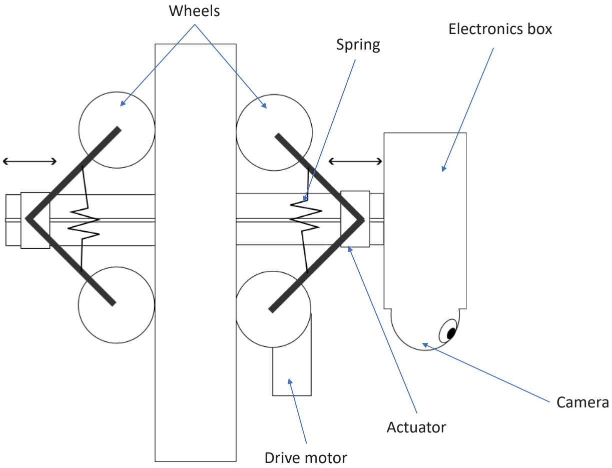

Fig. 5: Concept 1 - Parallel gripper

The second concept uses a claw-like motion to move two motor driven rotating arms, with wheels at the ends, to clamp onto the pole. A side and top view of this concept is shown in **Fig. 6**. The system has a driven wheel attached to the static base portion between the pivot points of the two arms. The arm motion will move on an arc and will contact at different points on different diameter poles but still allow for attachment to different base diameters. The two wheels attached to the end of these arms will be spring loaded to allow for changes in the diameter of the pole over its length. Active adjustment of the arms while traversing the pole could also be implemented.

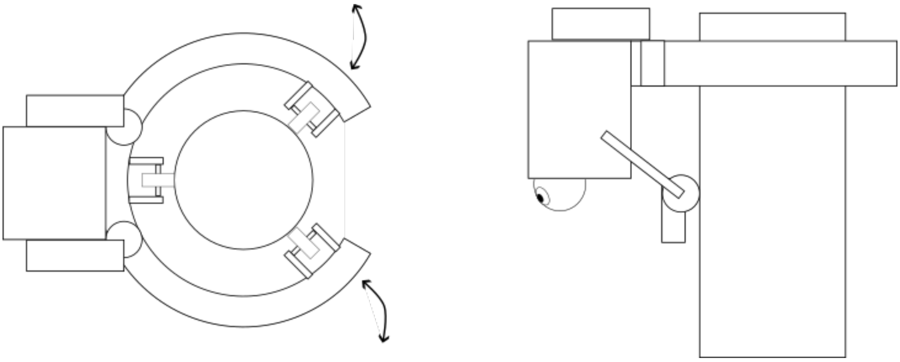

Fig. 6: Concept 2 - Claw

The third concept implements a natural gravity lock, that ensures that the drive wheel always has enough traction, independent of the weight of the robot if the centre of gravity is further than the minimum required distance away. The two cross members' length is adjustable to the base diameter of the pole, as shown in **Fig. 7**, and the system also implements a spring attached between two of the linkages to assist with change in the diameter of the pole over its length. At least one of the wheels will be driven to allow for traversing the pole.

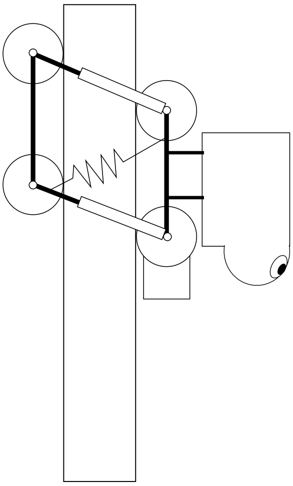

Fig. 7: Concept 3 - Gravity lock

After evaluation, concept 3 was chosen as the leading design. The concept design offered operational simplicity with no active control needed to adjust for obstacles and changes in diameter over the length of the pole. The concept also limited the amount of failure points that could cause a system to have an unplanned descent, as no actuator is used to attached to the pole, and a non-back drivable drive motor can be used as a redundancy for drive failure. The concept was then refined further to reduce complexity and weight. The number of arms and wheel pairs were reduced to only a single arm with one wheel pair. The spring was incorporated into the arm itself as this allowed for easier adjustment of the system. A diagram of the refined concept can be seen in **Fig. 8**.

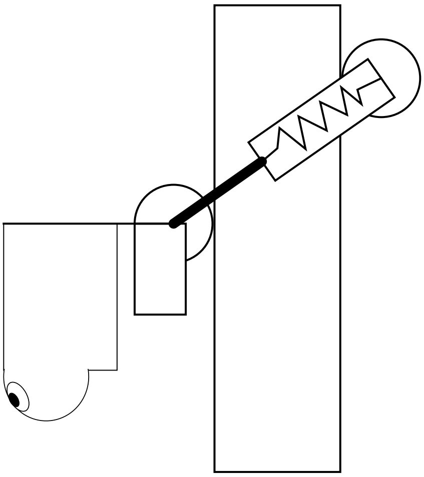

Fig. 8: Refined Concept3.1 – Gravity lock

The following sections will discuss the prototyping and detailed design completed on concept 3.

3.2 Prototype

Initial prototyping was completed to test the gravity-locking mechanism and to observe the effect of adding a spring, which allows for passive adaption to obstacles and changes in the size of the item clamped to. A small-scale LEGO® MINDSTORMS® [23] system was built with adjustable linkage length between the two contact points, front and rear, against the structural member, a square tube in this case. This generated experimental results on the effect of arm length versus the normal force at the contact point, which would represent the contact between the drive wheels and the pole in the final design.

A sliding joint and an elastic band, simulating a spring, were added between the two members, allowing the distance between them to be changed while attached to the structural member, a wooden beam in this case. The effect of the addition of a sliding joint and spring when moving over an obstacle or during dimensional changes in the structural member was then monitored, whilst different weights were attached to the system. Photos of the initial prototypes can be seen in **Fig. 9**.

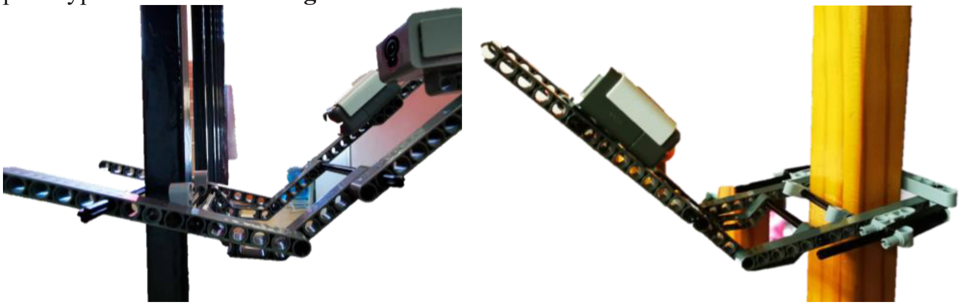

Fig. 9: a) Initial prototype without sliding joint b) with sliding joint and elastic band

A motorized prototype was also constructed to observe the behaviour when travelling up the pole. The prototype incorporated the same functionality of an adjustable linkage between the two sets of wheels and an elastic band on the one side. The motorised prototype was able to traverse up and down the pole and can be seen in **Fig. 10**.

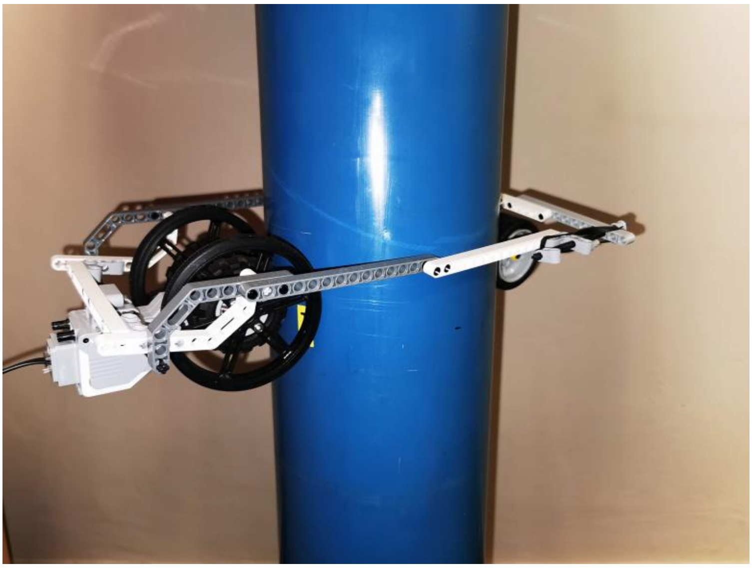

Fig. 10: Motorised prototype

3.3 Detailed design

The mechanical aspects of the project were designed using a combination of calculations using Engineering Equation Solver, Siemens NX computer-aided design (CAD) and simulations.

3.3.1 Calculations

A force diagram was set up of the robot to determine a safe distance the centre of gravity needs to be away from the contact point between the wheel and the pole, to generate the required normal force needed for traction, as seen in **Fig. 11** and **Fig. 12**.

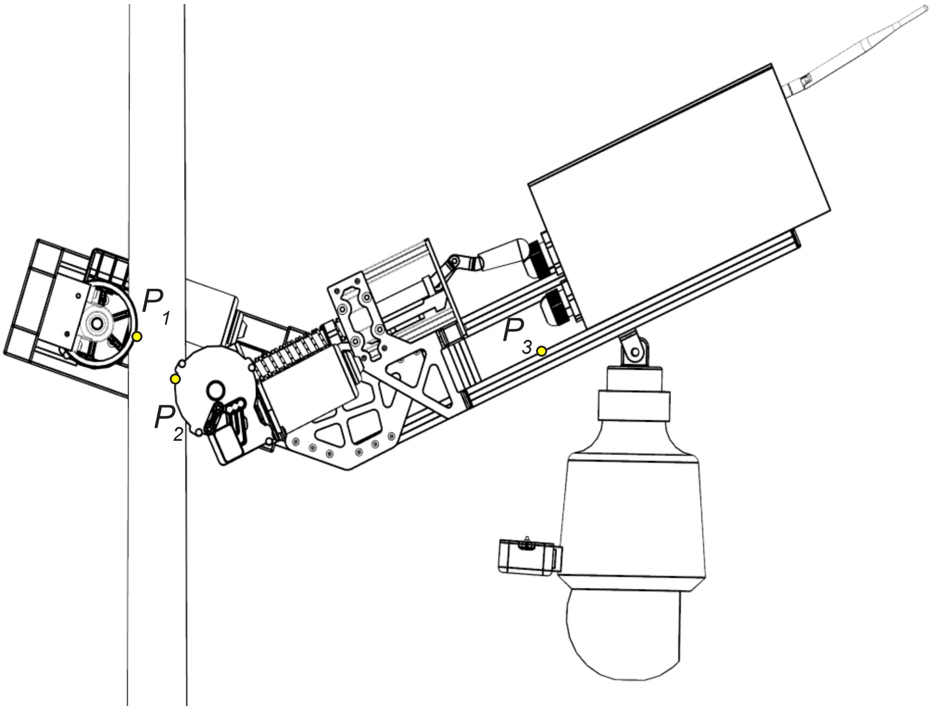

Fig. 11: Diagram of robot

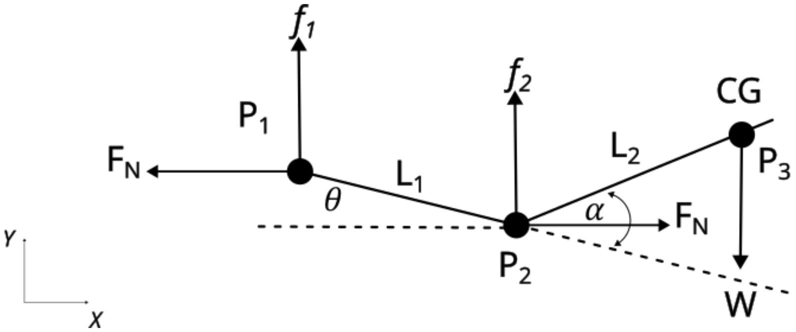

Fig. 12: Force diagram of robot

The variables, their descriptions and units can be seen **Table 1**.

Table 1: Variable description

Variable Name	**Description**	**Units**
F_N	Normal Force	N
f_1	Friction Force at P_1	N
f_2	Friction Force at P_2	N
W	Weight	N
L_1	Distance between contact points (P_1 and P_2)	mm
L_2	Distance between contact point (P_1) and centre of gravity (P_3)	mm
θ	Angle between P2 and P1	rad
α	Angle that P3 deviates from a line extending from P1 to P2	rad
μ_s	Static friction coefficient	-

Sum of forces in X direction:

$$\Sigma F_x = 0 \tag{1}$$

$$F_{N1} = F_{N2} = F_N \tag{2}$$

The condition for no slip to occur is:

$$f_1 \leq \mathrm{F_N} \times \mu_s \tag{3}$$

$$f_2 \leq \mathrm{F_N} \times \mu_s \tag{4}$$

From this we can assume the safe distance for L2 will occur when:

$$f_1 = f_2 = f \tag{5}$$

Thus, the minimum normal force needed is:

$$f = \mathrm{F_N} \times \mu_s \tag{6}$$

$$\mathrm{F_N} = \frac{f}{\mu_s} \tag{7}$$

Sum of forces in Y direction:

$$\Sigma F_y = 0 \tag{8}$$

$$2 \times f - W = 0 \tag{9}$$

$$W = 2 \times f \tag{10}$$

Sum of moments around P2:

$$\Sigma M_{P_2} = 0 \tag{11}$$

$$W \times \cos(\alpha - \theta) \times L_2 - F_N \times \sin(\theta) \times L_1 + f \times \cos(\theta) \times L_1 = 0 \tag{12}$$

By rewriting using (7) and (10) one gets:

$$2 \times f \times \cos(\alpha - \theta) \times L_2 - \frac{f}{\mu_s} \times \sin(\theta) \times L_1 + f \times \cos(\theta) \times L_1 = 0 \tag{13}$$

Eliminating f gives:

$$2 \times \cos(\alpha - \theta) \times L_2 - \frac{\sin(\theta) \times L}{\mu_s} + \cos(\theta) \times L_1 = 0 \tag{14}$$

Rewriting for the expression of L2:

$$L_2 = \frac{\frac{\sin(\theta) \times L_1}{\mu_s} - \cos(\theta) \times L_1}{2 \times \cos(\alpha - \theta)} \tag{15}$$

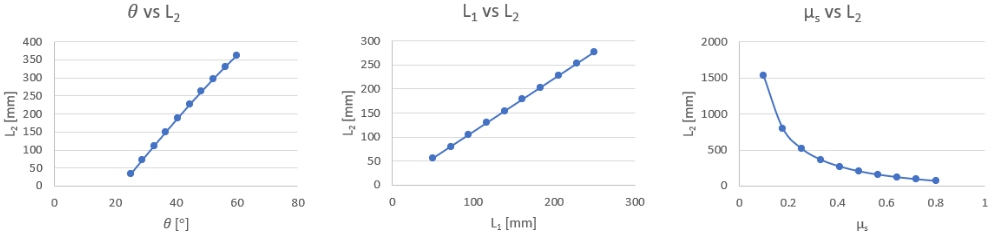

Fig. 13: Graphs depicting the effect of θ, L_1 and μ_s on L_2

From the calculations and graphs seen in **Fig. 13**, it can be established that a shorter arm distance (L_1), a smaller angle between P2 and P1 (θ) , and a larger friction coefficient (μ_s) all reduce the distance the centre of gravity needs to be away from P2 (L_2). The calculation results were then used in the creation of detailed CAD of the robotic system.

3.3.2 CAD and Simulation

The current detailed design consists of a frame comprising of aluminium extrusion members that are joined together. The electronic box, camera, spring loaded drive assembly and the adjustable arm assembly, with the secondary drive assembly, are attached to the frame. The design components can be seen in the labelled CAD image in **Fig. 14**.

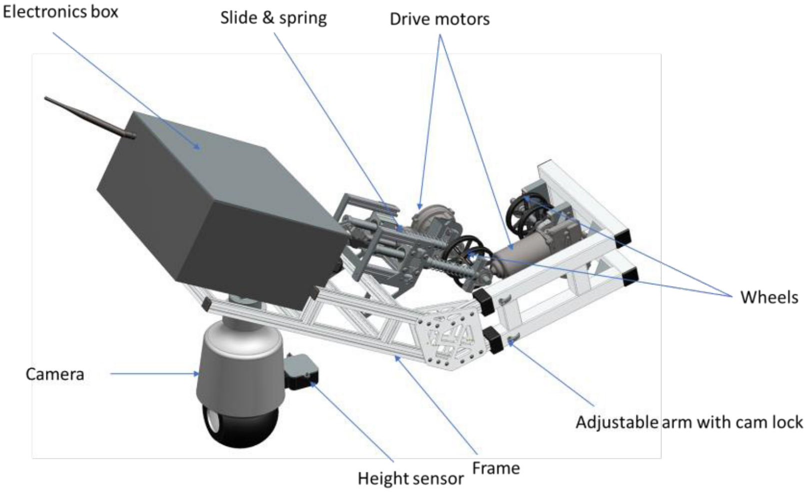

Fig. 14: CAD rendering of the proposed robotic platform ARGUS

The adjustable arm is guided by four plastic bushes that slide between the arm and the frame; it is locked in place by means of cam locks. This mechanism is used to attach the robot to the base diameter of the pole. The spring-loaded drive assembly consist of a bracket with two attached two linear bearings, mounted to the frame. The drive motor and wheels are connected to the linear rods that allow them to move relative to the frame, to overcome obstacles or changes in the pole diameter. The bracket also houses a lever arm that enables the operator to pre-tension the spring to the desired amount.

Wheel geared motors are used for the drive motors as they are non-reverse drivable, thus they do not require power to keep the robot in place after it has traversed up the pole. This also adds redundancy so that the robot will not fall if power is lost on the robot or motors. The motors are connected to the wheel with a flexible coupling connected to the wheel's shaft. The wheels are made of plastic, with a thin rubber tire for traction.

The camera connects to the frame with a bracket that has a pin hinge. This allows the camera to always level itself to the ground with a gimbal effect, due to gravity, as the robot frame angle relative to the ground changes if the diameter of the pole changes over its height. Friction was added to the pivot point to reduce any swinging of the camera. The height sensor is mounted onto the body of the camera to ensure it will always face perpendicular to the ground. A secondary view of the robot can be seen in **Fig. 15**.

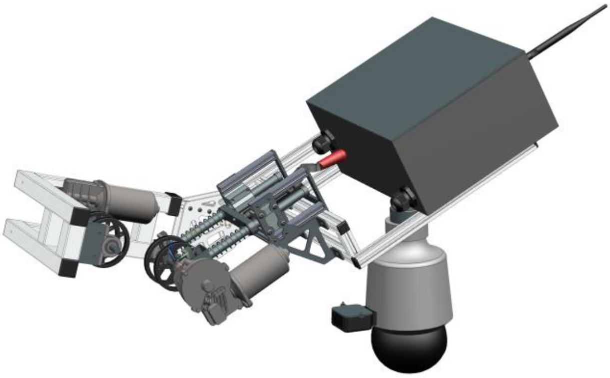

Fig. 15: CAD rendering of secondary view of ARGUS

Once the initial detail design was completed, multiple structural simulations were conducted using Finite Element Modelling (FEM) to ensure proper operation. A structural simulation was completed on the frame, as seen in **Fig. 16**, to ensure that the weight of the robot and payload as well as the forces of the wheels pressing onto the pole does not cause any adverse effects.

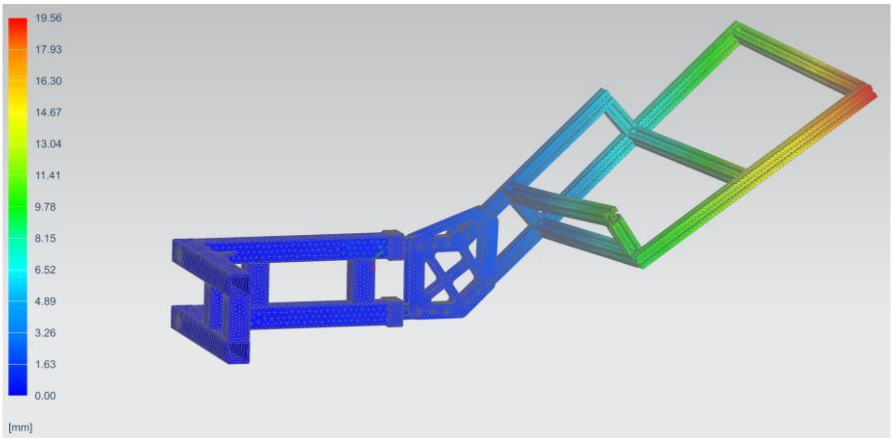

Fig. 16: FEM simulation of frame

Another simulation was done on the structural strength of the wheels and shaft while in contact with the pole, as seen in **Fig. 17**.

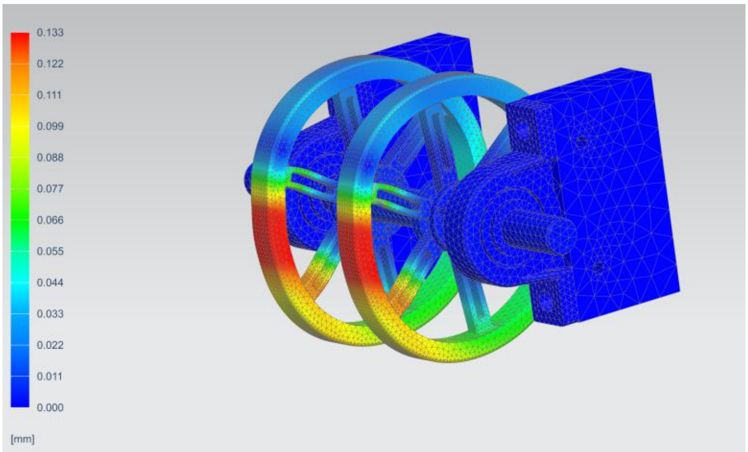

Fig. 17: FEM simulation of wheels

From the simulations it is evident that the displacement off the frame will not have a detrimental effect on the working of the robot. Some parts of the frame have large deflections, but the deflection between the two members on opposite ends of the pole will not cause loss of traction. It would still be beneficial to stiffen up the members that are experiencing large deflections. The simulation of the wheel show little to no deflection in the wheel assembly.

The electronic components housed in the electronics box and the corresponding software is described below.

3.3.3 Electronic and software design

In parallel with the mechanical design, the electronic and software design of the robot was completed, and a physical implementation achieved. The electronic design aspect of the ARGUS robot consists of a small hand build embedded platform that handles the interfacing to the motor controller and height sensor as well as providing power at the correct voltage levels for all the active elements in the system.

In the system's first iteration, a requirement was set for the device to remain operational for at least 4 Hours. The main voltage supply in the ARGUS Robot is determined by the 24 V motor voltage, and a solution needed to be found for a lightweight battery supply with sufficient power delivery. A power calculation of all system elements, including the use of motors for ascend and descend, arrives at an estimated 152 watt-hour (Wh) or 6.4 ampere-hours (Ah) at 24 V. A low complexity solution was found with some additional power margin in two 11 Ah LiFePO4 batteries with an integrated battery management system. Charging the battery system is done by applying a sufficiently powerful, current-limited, 28.8 V supply. The elements of the system are powered through several onboard power circuits, where the motor controller is powered directly from the batteries, and the other elements such as the system controller, sensors, and camera are powered from 5 V and 12 V DC/DC converters.

The interface to the robot elements is achieved via a Wi-Fi link and an internal Ethernet network. The RS-232 motor interface and RS-485 height sensor interface required a translation to Ethernet, and this was achieved using an Ethernet to UART converter in combination with a Raspberry Pi Pico controller board. For this hardware, Arduino code was written, which reads and writes the various serial interfaces, and that accepts JSON commands from the base station and returns JSON formatted status messages containing system and sensor status. The mentioned components can be seen in **Fig. 18**.

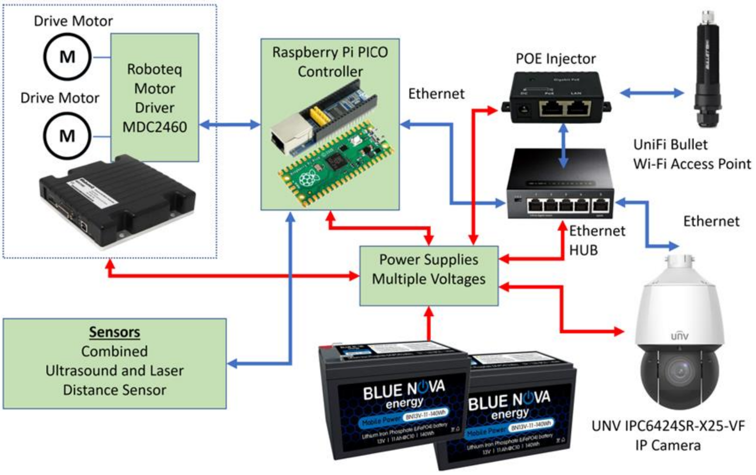

Fig. 18. ARGUS Electronic System Diagram

The main objective of the ARGUS platform is to perform situational observations, and this is achieved through a 4 Megapixel IP camera which is equipped with a Pan-Tilt mechanism and a powerful 25x zoom lens (PTZ). Control of the PTZ is performed via a built-in Open Network Video Interface Forum (ONVIF) interface command set, which is controlled by the base station software.

The base station software is implemented in Python code, making use of OpenCV and an ONVIF library. The user interface is kept as simple as possible, where the camera image is shown, and the operator can control the up-down movement of the robot as well as the PTZ function of the camera through defined keystrokes. Returned information of the height sensor and battery status are shown as an overlay on the image as seen in **Fig. 19**.

Fig. 19: Representation of camera feed

4 Conclusion

The literature study shows there is a need and high interest in rapidly deployable surveillance on existing infrastructure. A detailed design, comprising mathematical modelling, CAD simulation, and hardware selection was completed, culminating in the proposed design, known as ARGUS. The platform will be capable of carrying a payload of up to 5 kg and will be able to attach to poles with base diameters between 65 mm and 240 mm, whilst accommodating for a 40% change in diameter over the length. Critical sub systems, such as the wheels and frame, were simulated and shown to not deform outside of acceptable amounts for the operation of the system. The base concepts were also proven on a small-scale prototype.

The next phases in the project will be the integration of learnings from the simulations into the design, generation of manufacturing drawings, and the manufacturing of the first version of the robot for testing purposes. Once final manufacturing is completed, the platform will be completely tested, validating the system's design against the URS documentation.

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