A Review on Locomotion Systems for RoboCup Rescue League Robots

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Abstract A research paper was conducted in the Warthog Robotics group to gather information about robotic locomotion systems and some hybrid implementations on these designs. The purpose is to develop a new prototype to compete in the RoboCup Rescue League using the acquired data. This paper describes three fundamental locomotion systems (wheeled, tracked and legged) presenting a comparison to analyze their advantages and disadvantages. The presented hybrid and transformable locomotion systems have tracks and an actuator, such as wheels, legs or arms attached to its structure, and the capability to adjust its own tracks in different scenarios. A comparison was made regarding the needs of the competition, having systems recommended to each one of the relevant tasks in the scenarios proposed by the league.

Keywords: locomotion systems, rescue robot, tracked locomotion, hybrid locomotion, fundamental locomotion.

1 Introduction

Mobile robots are being constantly developed to substitute humans in rescue tasks, and therefore preventing people in hazardous environments. The RoboCup Rescue Robot League[1] collaborates with this evolution by encouraging research teams to compete in a simulated disaster area, resembling a post earthquake or tsunami scenario, with their developed robots, which need to be able to overcome obstacles and uneven terrains to find and rescue fictitious victims.

This research addresses the differences between wheeled, legged and tracked locomotion as well as their combinations and applications as an initial study for a future RoboCup Rescue League robot project for the Warthog Robotics research group from the University of São Paulo, Brazil.

This paper is organized as follows: Section 2 describes each fundamental locomotion system by itself, while Section 3 introduce some robot implementations of

[1] http://wiki.robocup.org/Robot_League

these systems combined in different ways, which are compared in Section 4 regarding a rescue scenario, and Section 5 concludes this research paper.

2 Differences between singular locomotion systems

In a dynamic environment, the locomotion system chosen for a robot needs to be well planned, since each locomotion system has its own advantages and disadvantages regarding energy consumption, mobility, speed and complexity. Considering that the robots mentioned in this paper have hybrid locomotion systems, it is important to be familiar with each individual configuration to determine which is better for each scenario.

2.1 Wheeled

The wheeled mechanism usually has advantages when running on smooth surfaces, where it can move at high speeds and with good performance in turning flexibility, while being simple to control and consuming less energy than a tracked mechanism [1,2], thus being highly recommended for flat surfaces. However, the mobility of the wheeled mechanism in uneven terrain is limited by the diameter of its wheels [2], which is a problem considering how chaotic a rescue scenario usually is, therefore it is not recommended for rough terrain.

Using wheels to overcome obstacles such as steps and stairs is not recommended as the wheel radius has to be greater than the obstacle height. For climbing and descending slopes, the slippage of the surface needs to be considerate, but in general wheels can be used for this task. Regarding gaps, wheels are highly not recommended as they need to be in contact with the ground to produce movement, and the contact length is minimal when compared to the tracked one.

2.2 Tracked

An alternative to overcome obstacles is the use of tracks for locomotion, war tanks are a good example of this. A robot using tracked locomotion can move robustly on rough terrain [3] due to its high adaptability to terrain conditions when compared to the wheeled locomotion [1], being highly recommended for this purpose even though it consumes more energy and moves at lower speeds [4,5], which is not payed off on flat surfaces. The track adds stability to the robot, decreases terrain pressure, has a simple control system, a prominent off-road mobility and allows the robot to climb higher steps than the wheeled does [6], being recommended when overcoming both steps and stairs. While on slopes, its friction assists on a stable movement, and on gaps the tracks rely on the size of the robot and its center of mass to avoid falling over.

The tracked locomotion can be divided into two categories according to its configuration: the fixed ones (F-track mechanism) and the transformable ones (T-track mechanism). The T-track mechanism was developed to fix the turning inflexibility and high power consumption presented in the F-track by adjusting itself to each soil and optimizing the track contact length with the ground [4].

2.3 Legged

A legged based locomotion is unstable and more complex to be controlled when compared to the previous ones [2]. Despite these disadvantages, legs can assist on high climbing (high steps and steep slopes) and on overcoming larger gaps than tracked or wheeled robots can, due to the ability to extend its legs to become body supports on the other side of the gap [3]. This characteristic allows legged robots to outperform wheeled and tracked robots in scenarios where there are abrupt discontinuities such as rescues in fallen buildings [1], therefore being highly recommended to overcoming both step and gap. The other important tasks for a rescue robot can also be performed by this mechanism in some way, even though there are options with less complex systems.

2.4 Comparison

The information displayed in this section is summarized in Table 1, where each one of the fundamental locomotion systems is rated for a series of tasks for a RoboCup Rescue League robot based on previous competitions and the scenarios shown in each one. The criteria used for this recommendations considers the ability to execute the task based on the literature and the geometric model of the robots, without considering its implementation or complexity. For example, the legged system has the ability to execute all theses tasks, but it has a high complexity and difficult implementation. The wheeled system can execute theses tasks as well, though the radius needs to be much larger than the tracked and legged actuators.

Table 1. Singular locomotion systems compared in relevant tasks for a RoboCup Rescue League competitor robot. Each system was evaluated as *highly not recommended* (HNR), *not recommended* (NR), *recommended* (R) and *highly recommended* (HR).

Tasks	Wheeled	Tracked	Legged
Overpassing a gap	HNR	NR	HR
Going through a step	NR	R	HR
Overcoming stairs	NR	R	R
Climbing and descending slopes	R	R	R
Moving on rough terrain	NR	HR	R
Moving on flat surface	HR	NR	R

3 Existing Hybrid Locomotion Systems

To expand the work field, some robots adopt two or more fundamental locomotion systems together, as can be seen on upcoming subsections. In this section, existing robots that use hybrid systems are studied individually regarding its characteristics and solutions for overcoming the challenges given in the competition.

3.1 MOBIT - the all-in-one robot

The MOBIT robot is designed to be compact, light, robust and energy-efficient by exploring the advantages of each locomotion system on each terrain condition [1], guaranteed by its capability to operate on wheeled, tracked and legged mode.

MOBIT has four independent legs attached to its body that can rotate 360 degrees with tracks along the legs length, which add versatility due to its degrees of freedom. Thereby, numerous locomotion modes are possible, as seen in Figure 1, where wheeled, tracked and legged mode are shown [1].

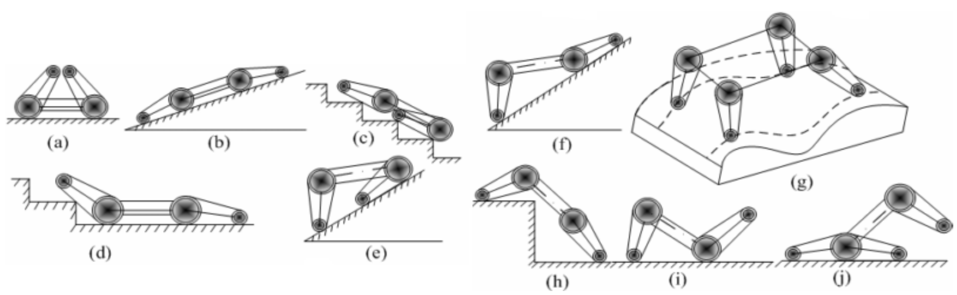


Figure 1. Possible locomotion modes of MOBIT: (a) wheeled mode; (b) and (c) possible stances to climb ladders and slopes in tracked mode; (d) initial stance when starting to climb a ladder; (e) and (f) stances to overcome steeper slopes by pushing the robot's center of gravity to a stable region; (g) legged mode; (h), (i) and (j) example of other modes that can be achieved with MOBIT [1].

A series of experiments conducted by Duan et al. [1] showed that the robot could reach 8.5 Km/h in wheeled mode opposed to the expected 10 km/h that were not achieved due to power supply weight. These experiments also mentioned the differences between stances shown in Fig. 1(b) and Fig. 1(c), which lay in its turning characteristic, because of their different structure and kinematics modules. Another relevant characteristic that was verified is the robot's capability of lifting itself up and moving in legged mode despite its weight that can reach up to 35 Kg.

The ability to climb stairs, to traverse steps and to recover after tipped over were also verified - the robot was able to overcome a 410 mm high step by using its tracked arms; a step greater than the length of the tracks (only 350 mm).

3.2 Quadruped tracked robot with manipulative legs

Developed by Fujita et al. [3] , the robot has two tracks and four legs that are capable of not only assisting movement, but also manipulating objects and obstacles. The number of legs could be six or more to guarantee a more stable gait, but its mobility would be affected by the weight increase and energy consumption [3].

Regarding the robot's mobility, it can move in track movement at a 500 mm/s maximum speed; overcome large gaps that would be impossible for a tracked-only robot to overcome; and its legs can assist at climbing high steps and steep slopes.

The capability to overcome gaps is deeply studied by Fujita et al. [3] along with the manipulation process to lift boards and retrieve objects, as seen in Figure 2(b).

The results in Fujita et al. [3] experiment show that the locomotion speed over a gap is 150 mm/s and the robot can run over up to 300 mm: 2.5 times the result of a tracked-only robot and 77% of the robot length. The robot was capable to lift a 900 mm board weighting 1 Kg laid obliquely on an object which was 500 mm high, retrieving successfully a target object of 115 g.

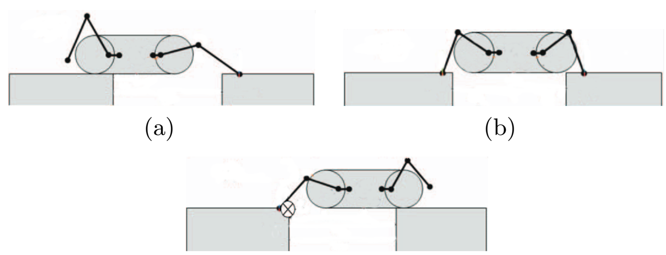


Figure 2. A quadruped tracked robot overcoming a substantial gap. Extract from [3].

3.3 Wheel-track mobile robot with retractable track

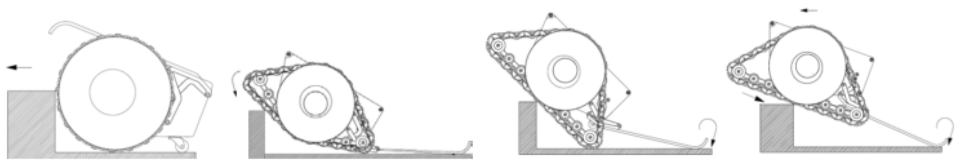
Considering both the adaptability of a tracked locomotion system to different soils, and the efficiency of a wheeled one, a retractable track locomotion system was envisioned by Guo et al. [2]. This transformable wheel-track works by expanding and retracting its track for tracked and wheeled modes, respectively, thus creating the need for a track made of a material with low elastic modulus. Adopting a transformable mechanism instead of a hybrid system that switches between locomotion modes saves weight and space [2].

The wheel-track unit is composed of two rotating gear rings that mesh with the track to transmit large force on tracked mode. In wheeled mode, the gear rings engage with parts of the track teeth to rotate together. It also has a sub-arm capable of assisting the robot in tracked mode to overcome high obstacles.

Analyses of the step-climbing ability of the robot were conducted, in which it was able to overcome obstacles that were no more than 80 mm high in wheeled mode, needing to change to tracked mode to climb higher obstacles with the assistance of a sub-arm located on the robot, being able to overcome a 240 mm obstacle. For comparison, the radius of the gear ring was 165 mm and the sub-arm length was 450 mm [2]. In regard to the soil differences, although the tracked mode presents a higher traction apart, the difference is relatively small on soils with low cohesion, such as snow and dry land, while in high cohesion soils, such as sand and clay, the track's traction is bigger than the wheel's.

A second generation of the robot was developed with improvements on the track and tests were conducted in grass and clay [6]. In wheeled mode at low speeds the robot was capable of running without slipping (no more than 0.3 m/s). With torque increase, the robot slips proportionally to the torque. For tracked mode, the adhesive force is large enough to avoid slips. The Wheel-Track Transformation Robot (WTTR), as it is called [5], works in a similar way, but with an sub-arm as an extra support mechanism used to climb steps, as shown in Figure 3. Hu et al. [5] also mentions locomotion strategies to overcome obstacles that can be faced in a scenario formed by disasters: climbing a step, traversing a gap and escaping a groove.

To climb a step, the robot simply expands its tracks to engage in tracked mode and extends its support that assists rising up the robot's rear end and crossing the obstacle successfully. To transverse a gap, the tracked mode is also useful as the contact area with the ground is larger than the wheeled mode, decreasing pressure. In case of the robot getting stuck at a groove in wheeled mode, it can expand its tracks and assume the same state as the one used to transverse a gap.



(a) Robot contacts step (b) Robot adapts to the height of step (c) Track completely expanded (d) Climb a step

Figure 3. Wheel-Track Transformation Robot (WTTR) process of climbing a step [5].

3.4 Transformable wheel-track in NEZA-I and Amoeba-III

The NEZA-I [4] and Amoeba-III [7] are similar projects conducted by the same authors and can be analyzed together as they both have the same locomotion system - a self-adaptive mobile mechanism with two symmetric transformable wheel-track (TWT) units that make changing locomotion mode and transforming the track configuration feasible, as it is illustrated in Figure 4. This adaptation occurs autonomously by the constraint force information, which improves the efficiency of the motors and simplifies the operation.

On flat and rough terrain, the robot contacts the ground by wheel and track, which can be considered as an imaginary wheel due to it being tangent to the ground. This minimizes the contact length, providing turning flexibility and saving energy. When in track mode, only the tracks are used for locomotion, which can be adjusted and therefore can change the locomotion posture to overcome different obstacles.

3.5 Tracked robot with manipulative arm

Tracked robots that have manipulative arms often have problems to move under short heights and to perform when flipped over. Considering this, Ben-Tzvi et al. [8] developed and studied a tracked mobile robot with manipulative arms integrated

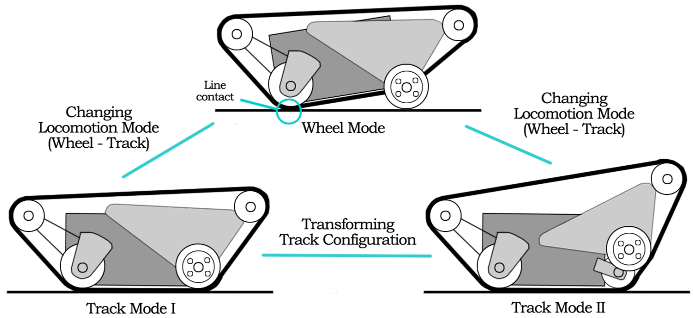


Figure 4. The NEZA-I and Amoeba-III scheme to change locomotion mode and transform its track configuration [7].

to its base so that the robot becomes sturdy and capable of moving and using the arm on both sides.

Beyond the basic actions that a manipulative arm can perform, this arm specifically was designed to be able to assist locomotion in a similar way that the sub-arms described in Subsection 3.3 do, as shown in Figure 5. The arm is composed of two parts that are linked and represented by orange and blue colors in this figure, with the blue one being the innermost one.

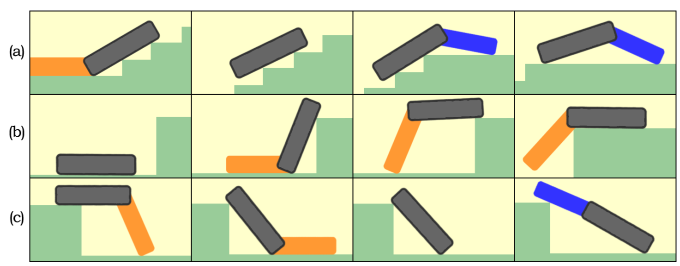


Figure 5. The track robot with manipulative arms in four different situations which the arm can be used to assist locomotion: (a) climbing stairs; (b) climbing a step; (c) descending a step [8].

3.6 Rocker-Bogie Suspension

Developed by NASA[2] and used on two identical rovers sent to Mars in 2004, this mobility system was designed to meet some requirements, such as traversing 25 cm high obstacles, overcoming sloped terrains in any variation between 0 and 20 degrees tilt and traveling distances superior to 1 km over hard high traction terrains and soft deformable soils [9].

[2] https://trs.jpl.nasa.gov/handle/2014/38435

The rovers are equipped with six independently actuated wheels, with the front and rear pair being steerable, allowing the robot to execute maneuvers such as turning in place and arc turning. Besides this, each wheel has cleats that assist the rovers to climb in loose soil and traversing over rocks as high as the wheel diameter. On flat hard ground, the top speed of these robotic spacecrafts is 4.6 cm/s, which is not used on Mars due to an autonomous control with hazard avoidance [9].

The rocker-bogie suspension is represented in Figure 6, showing only the left side of the structure. The six wheels are connected to the body of the rover with this mechanical configuration with a differential mechanism attaching the left and right sides that enables the robot to passively keep all of the wheels in contact with the ground even on severely uneven terrains, keeping the wheels pressure on the ground balanced, avoiding sinking in soft soil due to excessive pressure. Furthermore, all six wheels being in contact with the ground can help the movement when climbing hard uneven terrain, maximizing the vehicle's motive force capability by actuating each wheel independently. This suspension is also capable of absorbing significant energy from driving loads and, with the center of mass being near the pivot point of the suspension, the rovers can withstand a tilt of 45 degrees in any direction without overturning.

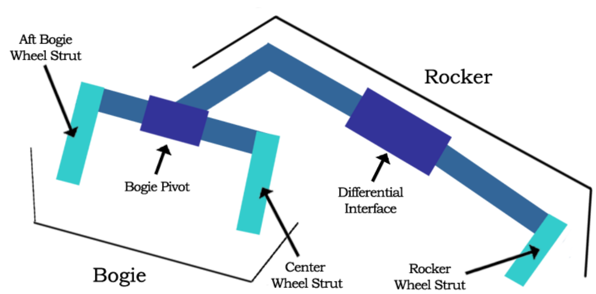


Figure 6. A simplified representation of the left side of the rocker-bogie suspension structure used on both Spirit and Opportunity NASA rovers sent to Mars in 2004. This suspension allows the robot to passivelly keep all six wheels in contact with the ground. Detailed structure is available in reference [9].

Tests were conducted by Lindemann et al. [9] in slopes with angles between 0 and 20 degrees at different orientations in two different surfaces: one being a high friction mat with obstacles up to 25 cm high and the other one being the same mat with dry loose sand on top. On the first one, the robot was able to climb over obstacles up to 15 cm high on all slopes, and up to 20 cm high on slopes with angles between 10 and 15 degrees without excessive wheel slippage. In the soft soil, the rover sinks down between 1 and 2 cm, increasing to as much as 12 cm while traversing obstacles over 15 cm high, increasing the energy consumption due to soil work. The fact that Spirit was working on Mars until March 22, 2010 and

Oppotunity is still working (last update was on March 21, 2017)[3] also validates the efficiency of this mechanism.

3.7 Mecanum Wheels

Although a wheeled robot isn't suitable for a disaster environment such as the proposed by the Robocup Rescue League, it is interesting to notice the possibilities that mecanum wheels can add to an hybrid project (such as the legged-wheeled hybrid studied by Fujiya et al. [10]), considering that the omni-direction feature can save time and space to perform maneuveurs. Figure 7 shows how the primitive moves can be achieved in a four wheeled robot, although it is possible to use only three, which could cause the robot to tip over more often [11].

Besides the inability to work in irregular surfaces, as any wheeled locomotion system generally is, the mecanum wheel has some problems regarding slippery areas due to slippage [12] and moving in rough terrains that can cause sand or dirt to pile up on the side of the wheels, preventing the robot to move laterally. This latter problem can be solved by modifying the angle of each roller and by using a combination of two wheels where it would be used only one, as seen on [13].

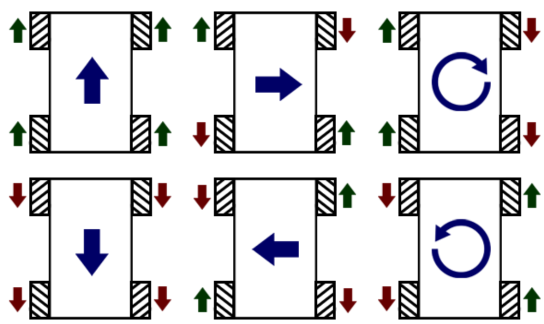


Figure 7. Primitive moves for a mecanum wheeled robot with four wheels. If all wheels go to the same direction, the robot goes forward or backwards (first column of the diagram). If only the diagonals do so, the robot goes left or right (second column). Otherwise, if each side of the robot goes to one direction, as shown in the third column, the robot rotates [14].

4 Comparison between locomotion systems

For comparing the locomotion systems studied in this paper, it is necessary to create comparison parameters. Considering that the objective comprises of satisfying the Robocup Rescue League challenges, the required capabilities are: overpassing gaps; going through steps; overcoming stairs; climbing and descending slopes; moving on rough terrain and on flat surfaces.

[3] https://mars.nasa.gov/mer/mission/status.html

Overcoming wide gaps requires that the robot have a support on the opposite side of the gap, otherwise it will fall down when its center of gravity exceeds the edge of its current platform [3]. Following this thought, the quadruped tracked robot, as seen in Figure 2(b), has advantages over the others, as it is the only one to have proper legs for this purpose, thus being highly recommended for this task. The MOBIT is also recommended to this task, as it can use its tracks as legs for this purpose, however it doesn't have the same flexibility. For the transformable wheel-track robot with retractable track, the gap must be shorter than the size of the robot itself, which then can expand its tracks to escape a groove and is not recommended for this task solely, even though it is a solution to an eventual stick. The other two robots left can overcome gaps only if the condition of the center of gravity not exceeding the edge is matched, therefore not being recommended when facing wide gaps [3]. The rocker-bogie and mecanum wheel are not suitable for this task, as the wheels need to be in contact with the ground to produce movement, therefore they are highly not recommended for this task alone.

Regarding steps, all robots presented in this paper can perform well and are recommended for this task, but in different ways and heights, which is severely influenced by the robot height as well. Robots like the quadruped tracked and the one with manipulative arm (Fig. 5) can easily overcome obstacles due to the assistance that their legs or arm provide, thus being better solutions than the others. For the others, rocker-bogie suspension allows the robot to overcome steps as high as its wheel diameter, while the other robots mentioned surmount this by adjusting their tracks heights and inclination. The same principle is used to climb stairs, in which case the quadruped tracked robot can use its tracks for this purpose if it is better suitable, with the MOBIT also being highly recommended as the versatility of its legs can adapt it to better accomplish this task as displayed in Figure 1. For the mecanum wheels, only thin steps can be surpassed according to the wheel radius and the rollers radius, thus being highly not indicated for those tasks.

For slopes, the robots presented can perform well both on climbing and descending, as the track can be used to improve adhesion to the ground and the rocker-bogie was approved in tests for slopes tilted up to 20 degrees. The mecanum wheels can be used to descend a slope, but many things need to be taken into consideration for the mechanism to ascend a slope, such as inclination and slippery, thus being not recommended when overcoming slopes is important [15].

The robots can operate well in rough and uneven terrain using its tracks as supports, being the ones with some kind of support, such as MOBIT, the quadruped tracked and the tracked arm highly recommended as they can easily overcome eventual sticks. Even though, for flat surfaces wheeled mechanisms are highly recommended due to reduced contact surface (reducing friction), thus increasing speed and saving energy. Rocker-bogie is highly recommended for both cases, as it is designed to work properly on rough terrain even though it uses wheels, which has been proven as rovers working on Mars use this mechanism. It is important to notice that, even though the mecanum wheel enables the robot to easily move in any direction as seen in Figure 7, it consumes more energy than a normal wheel as the movement of a mecanum wheel sometimes isn't completely used to move the robot to the same direction. The tracked with arm is not recommended to work on flat surface as it does not have a mechanism to reduce the contact area with the ground, while the other robots have. This discussion is summed up on Table 2, in which the robots are classified for each required capability.

Table 2. Recommended locomotion systems for each specific task: Overpassing a gap (I), going through a step (II), overcoming stairs (III), climbing and descending a slope (IV), moving on rough terrain (V) and moving on flat surface (VI). Each system was evaluated as *highly not recommended* (HNR), *not recommended* (NR), *recommended* (R) and *highly recommended* (HR).

Tasks	MOBIT	Quadruped Tracked	WTTR	NEZA-I and Amoeba-III	Tracked w/ Arm	Rocker-Bogie	Mecanum Wheels
I	R	HR	NR	NR	NR	HNR	HNR
II	R	HR	R	R	HR	R	HNR
III	HR	HR	R	R	HR	R	HNR
IV	R	R	R	R	R	R	NR
V	HR	HR	R	R	HR	HR	HNR
VI	HR	R	R	R	NR	HR	HR

5 Conclusion

In chaotic environments, such as the proposed in the RoboCup Rescue League, versatility is a key feature to success. Robots that combine the three locomotion systems mentioned in this paper can adjust themselves to benefit from the advantages of these architectures and avoid the disadvantages by switching systems.

To guarantee a good range of mobilities, a track-legged hybrid was suggested, as this combination adds the capability to move in rough and irregular terrains while overcoming obstacles, steps and gaps. Although the wheeled locomotion is not mandatory for this environment, it delivers speed and saves energy when compared to the tracked one, while being easier to control and more stable than the legged system, so it can be useful if it is possible to implement wheels in the project. Therefore, the quadruped tracked robot and the MOBIT have recommended mobility architectures for a rescue environment.

Future work in this field will include other locomotion systems, such as hexapod robots, hopping mechanisms and softrobotics actuators[4].

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[4] https://softroboticstoolkit.com/actuators

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