Bi-pedal Robot for Rescue Operations

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Abstract— **Wheeled and tracked vehicles are mainly suitable for relatively flat terrain. Legged vehicles, on the other hand, have the potential to handle a wide variety of terrain. This article presents a new locomotion concept, adapted to both flat and complex rough terrain by combining the advantages of wheeled and legged vehicels. MATE-1 is a bipedal robot equipped with two special grippers which provide the capability of walking and climbing in rough terrain and rolling on smooth surfaces. A subtle design of the robot's mechanical structure allows combining different locomotion concepts, thus increasing its mobility and its capacity to adapt to the terrain without exceed in weight or size.**

Keywords— **robot, bi-pedal, climbing, walking, claw**

I. Introduction

There are several applications where robots have to deal with rough terrain and standard locomotion concepts cannot be used. The main fields are without doubt rescue operations and exploration tasks where robots are sent into dangerous environments or inaccessible and unreachable places for humans. Rescue robots and planetary exploration machines need to show strong off-road capabilities due to the unstructured environment met during their mission. The fact, that such a difficult environment requires a highly adaptable mechanical structure and a complex control system has motivated a lot of researchers to develop flexibles locomotion concepts which are capable to deal with this kind of terrain. However, these robots still have often limited climbing abilities. Therefore, a new and more flexible locomotion concept has to be found which could be used for rescue operation. In response to this requirement a small Multiactuated All-Terrain Explorer (MATE-1) has been designed, constructed, and evaluated (Figure 1).

MATE-1 is a bipedal robot which is adapted to both smooth and complex rough terrain. Its flexibility is due to a subtle foot-desing: its grippers allow grabbing structures with a width smaller than 60mm and provides the required hold when moving in rough terrain, thus ensuring the stability of the motion when the robot is "walking". Furthermore, the grippers can be used as whegs [1] for locomotion on smooth surfaces.

The purpose of this paper is to illustrate the design, implementation, and evaluation of this small bipedal robot. Section 2 reviews rough terrain and climbing robots in the literature relative to MATE-1. Section 3 presents design constraints and in Section 4 kinematic structures are dicussed. The mechanical design of the robot is presented in Section 5 and its control is discusses in Section 6. Section 7 evaluates the performances of the robot while moving in rough terrain and on smooth surfaces. A review of future work and concluding remarks are given in Section 8.

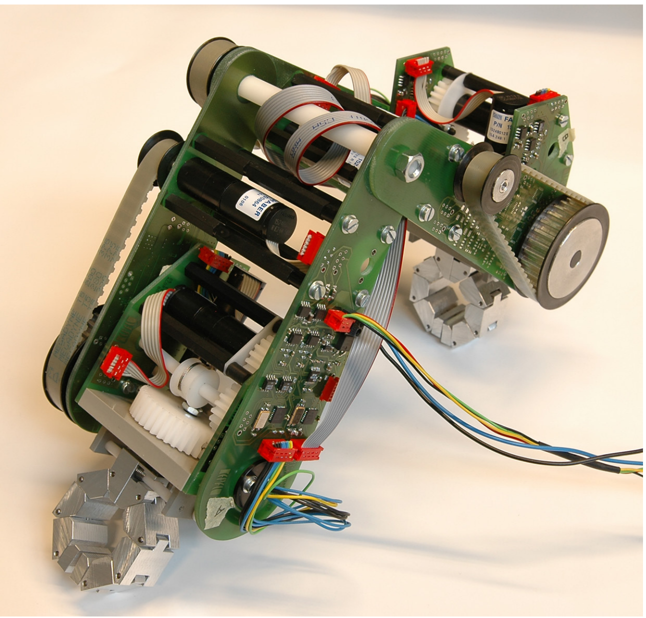

Fig. 1. Multiactuated All-Terrain Explorer (MATE-1)

II. Rough terrain and climbing robots

A classical solution for moving in rough terrain is to use tracks for locomotion, e.g. the iRobot Packbot [1]. Those vehicles demonstrate good off-road abilities because of their stability and good friction coefficient during motion. The mechanical structure and the control of a track system are simple, but the friction losses between the surface and the tracks when the robot is turning are high. Furthermore, the system does not offer enough mobility to overcome high obstacles or move in every direction.

Wheels are also used for locomotion in rough terrain and special configurations offer a high degree of adaptability. Hence, a passive compliance structure e.g. the Shrimp developed by Swiss Federal Institute of Technology [2] is able to overcome obstacles twice the diameter of its wheels. However, this robot can hardly deal with obstacles like cables or bars like those found in collapsed buildings.

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[1] Fusion of wheels and legs: the rotation of legs drives the robot forward.

The flat terrain speed and efficiency of wheeled robots has led some robotics researchers to blur the line between wheeled and legged machines to increase their ability to move in restricted environments. A powerful example is the RHex [3]. It is the first documented autonomous legged machine to have exhibited general mobility (speeds at body length per second) over general terrain (variations in level at body height scale). Yet, this robot is not capable to overcome obstacles exceeding its body height and it cannot move in any direction.

Walking machines are in general well adapted to unstructured environment because they can insure their stability in a wide range of situations. However, their mechanical complexity requires a lot of control resources and they demonstrate low speed motion and high power consumption if compared with the other solutions. Quadruped as ROSTAM [4], NINJA-1 [5] and ROBUG II [6] and higher legged robots as ROBUG III [7] and MSIV [8] provide increased stability and load capacity. The control of these robots is more complicated and they are typically much larger. The trade-off is increased size, complexity and weight. When compactness and efficiency are critical, as in MATE-1, a structure with minimal weight and complexity is best applied. For these reasons, the biped format is an excellent candidate.

Most biped robots use similar ankle structures where articulation is provided to both feet and steering to at least one foot. Bipeds vary most appreciably in the style of their middle joints. Robots using a revolute middle joint, similar to MATE-1 include the robot RAMR1 [9] and the robot ROBIN [10]. A prismatic middle joint is used by ROSTAM IV[ROSTAM], whereas Yano [11] and Roma 2 [12] apply a rigid central body.

The main difference between MATE-1 and the aforementioned biped robots is the robot's foot design. Whereas most biped robots use suckers or magnetism to grip flat surfaces, MATE-1 and Roma1 [13] are equipped with two grippers that adaptively grasp different beams and columns.

Beyond similarity in the holding mechanism, the grippers of MATE-1 possess several characteristics and features not found in the foot design of Roma1. First, the grippers can adapt passively on de structure being gripped, which increases the robot's capability to take hold on different structures. Furthermore, the grippers can be used as whegs (wheels + legs) for locomotion on flat surfaces, thus improving the capacity of the robot to deal with different kinds of terrain.

III. Design Requirements

The purpose of MATE-1 is to test a new locomotion concept which is adapted to both flat and complex rough terrain. The scenario which has been chosen as a typical application of the robot is a rescue operation inside a collapsed structure after an earthquake. Indeed, the victim survival rates might be increased by fielding teams of collaborative robots which can negotiate compromised and collapsed structures and search for victims. Such teams of robots could be used in situation where the search is either too dangerous (fire, instable structure) or impossible (too small space) for men. The robot has therefore to be capable of dealing with a complex environment which consists of obstacles of different materials and shapes such as beams, bricks or broken windows. Furthermore, it has to be able to move on flat surfaces as well, since some parts of the buildings might still be intact. The robot must be sufficiently small to travel through confined spaces, but big enough to overcome small obstacles. As an autonomous system, the robot will eventually carry its own power source, processor and sensors. Thus, minimisation of power usage and weight are critical to prolonged operation.

This first prototype is remote controlled through a control interface and manipulated with a gamepad to expedite the controller developments. Given these allowances and the mission scope of MATE-1, the following design criteria have been established:

- Mobility. The robot must be capable of walking and climbing on complex rough terrain, rolling on flat surfaces and navigate between specified locations.
- Size. The robot should occupy a space less than 30cm x 10cm x 10cm.
- Space Requirements. The robot should be able to pass through restricted areas with a cross-section of 15cm x 15cm.
- Weight. The robot should be able to lift its own weight in any position at any time.
- Control. The robot is remote controlled with a gamepad allowing a flexible and adaptive manipulation of the robot.

IV. Kinematic design

Several candidate designs were considered prior to selecting the format of MATE-1. A number of different locomotion concepts adapted to unstructured terrain were evaluated in order to identify a promising solution. The general biped structure was chosen for its simplicity and high degree of mobility without excessive weight or size. Within the biped format, several kinematic designs were considered. The primary variation was the strategy used for locomotion on flat and rough terrain. Each solution is predisposed to a particular way of progressing that directly influence the mobility of the robot and its space requirements. Whereas in complex rough terrain, claws appear to be a promising solution, they cannot be used on flat ground. Wheels, on the other hand are particularly adapted to flat surfaces, but cannot deal with unstructured terrain. Hence, a combination of the two concepts would be ideal.

Six structures combining these two means of locomotion have been studied and their characteristics have been quantified and summed in weighted proportions to determine an optimum design. The criteria for selecting the kinematic structure are: the numbers of actuators, the mechanical simplicity, the possibility to orient the grippers, the smoothness of transition between locomotion on rough terrain and locomotion on flat surfaces and the convenience of changing direction when moving on flat surfaces. The final choice is a structure equipped with grippers that can be used as whegs and claws (Figures 2 and 3).

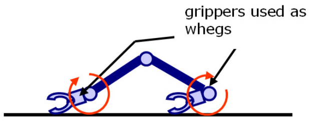

Fig. 2. Gippers used as whegs

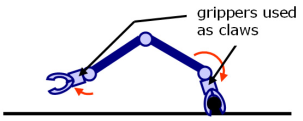

Fig. 3. Grippers used as claws

A. *Locomotion modes*

The robot can use different modes of locomotion which are described below. They improve the adaptation to the environment and therefore the capability of the robot to deal with unstructured terrain as well as flat surfaces.

Wheg-mode: Since the rotation of the gripper is unlimited, it can be used as wheg. With this mode of locomotion, the robot can move faster on flat or nearly flat ground (Figure 4). The major difficulty of this mode is changing direction. This is only possible by stopping the rotation of the gripper and rotating the prehensile claw perpendicular to the previous rotation (Figure 5).

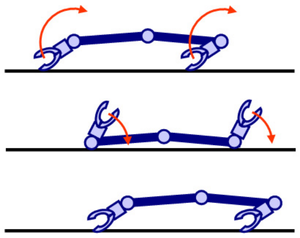

Fig. 4. Wheg-mode

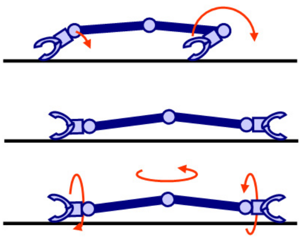

Fig. 5. Change of direction in wheg-mode

Turn-mode: Turn-mode is the robot's basic mode of locomotion in rough terrain. It allows for fast movements since only one motor has to be controlled. The step size is bigger than in inch-worm-mode and the robot needs less vertical space than in either of the other rough-terrain-modes. Hence it could be used to pass under obstacles in height. Unfortunately it requires a huge horizontal space and can therefore only be used where the area is not too restricted.

Flip-mode: If the space is limited horizontally but is large enough vertically, the robot can use flip-mode for locomotion. It offers a big step size as well, but requires a better coordination of the motors and is therefore more difficult to execute and slower. Nevertheless, it can be very interesting, especially for transitions between tilted surfaces or for passing over small obstacles.

Inch-worm-mode: Inch-worm-mode is used for small diplacements or if the robot does not have enough space for the other rough-terrain-modes.

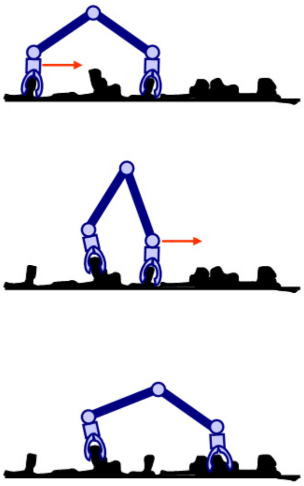

Fig. 6. Inch-worm-mode

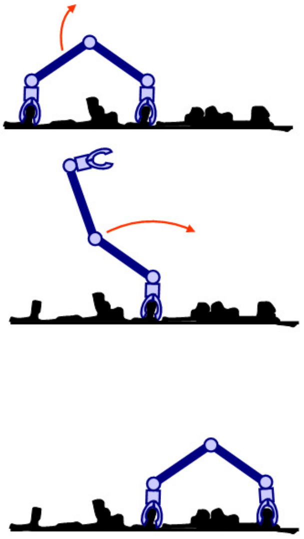

Fig. 7. Flip-mode

The step size is smaller and slows down the overall speed of the robot. Its main application will therefore be when the robot has to go through narrow passages.

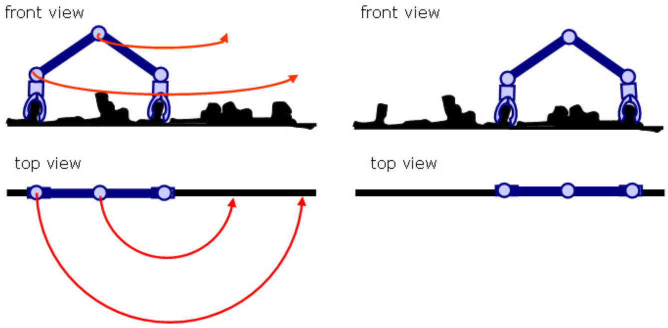

Fig. 8. Turn-mode

It is clear that a combination of different locomotion modes is possible. It would certainly improve the adaptability of the robot to the terrain, but increases the complexity of the movement. In the end, the movement of the robot MATE-1 depends mostly on the ability of its manipulator since it is remote-controlled.

V. MECHANICAL DESIGN

A bipedal robot must have at least five degrees-of-freedom (DOF) to transit between two surfaces of any inclination. MATE-1 has therefore been equipped with five actuators for the base movement and two supplementary actuators for the opening and closing of the claws. Figure 9 presents the final structure of the robot. Its base consists of two thighs connected through the axis a_{M1} and equipped with a gripper each.

A. *Base structure*

The first degree-of-freedom of the robot is the rotation of one thigh with respect to the other around the axle a_{M1}. The angle between the two thighs is controlled by the motor M1. It can vary between 68°

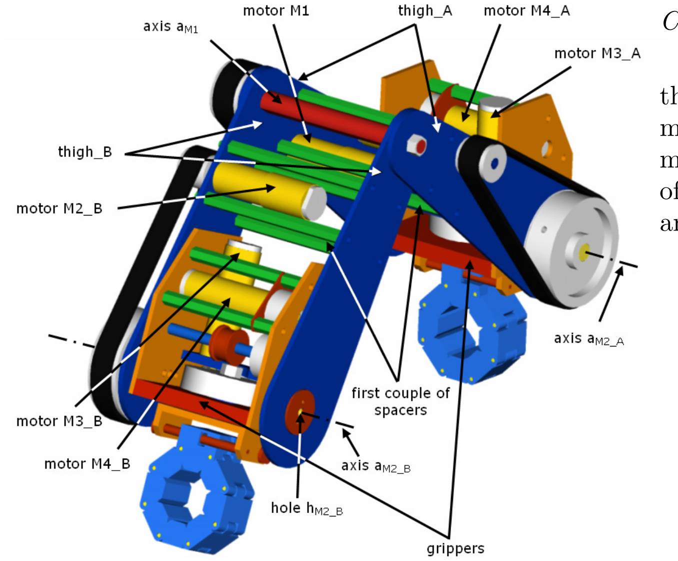

Fig. 9. Final design of the bipedal structure

and 428° and is limited by software and hardware. The hardware limitation is made with two spacers on thigh_B which also serve as butts.

The second and third degree-of-freedom are the rotation of the grippers relative to the thighs around axis a_{M2_A} and a_{M2_B} respectively. The distance between these axis and the first pair of spacers is defined by the gripper size. This space has to be large enough to allow for rotation of the gripper between the thighs. In theory, the rotation of the grippers is unlimited. Nevertheless, the actual rotation should not exceed ten revolutions since electric wires will pass through the holes h_{M2_A} and h_{M2_B}.

B. *Grippers*

The grippers are made up of three parts (Figure 10): the gripper base, the gripper head and the claw. The gripper base is fixed to the rotational axis a_{M2_A} and a_{M2_B} respectively. It includes two actuators with their corresponding chains of transmission controlling the last four degrees-of-freedom.

The fourth and fifth degrees-of-freedom of MATE-1 are the rotation of both gripper-heads around the axis a_{M3_A} and a_{M3_B} respectively. They are controlled by the motors M3_A and M3_B, the movements of which is limited by software only.

The motors M4_A and M4_B each control a claw. These two claws are the sixth and seventh degrees-of-freedom. The rotation of the motors is transmitted by two gears to a pulley which coils up the cables connected to each claw as described in next subsection.

The completed prototype of MATE-1 weighs 1050 grams. The dimension of the robot in its longest configuration is 33cm x 10cm x 5cm. The robot meets mobility requirements, but it is not well suited to extremely confined spaces.

C. *Claws*

The claws are the connection between the robot and the ground. They provide the grip required for movement. Hence they should be able to grip strongly as many different shapes as possible. An intensive study of the optimal claw shape had to be carried out to find an adequate solution.

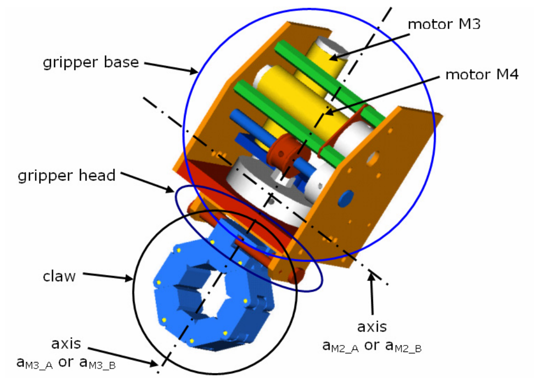

Fig. 10. Final design of the bipedal structure

The final design of the claw is shown in Figures 11 and 12. It consists of two fingers with several solid segments connected by axles and cables. The segments are pushed apart by springs. When the cables are pulled, the segments approach each other and the claw closes. The particularity of this claw is its two levels which allow for gripping small and bigger structures. The first claw level (Figure 11) is able to grip structures whose width is smaller than 20mm. The second level is used for structures with a width between 20mm and 60mm (Figure 12). If the first level is used to grab, the second level can provide a supplementary hold. Both claw levels are controlled by a single motor pulling the cables.

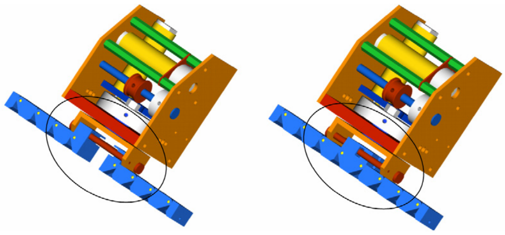

Fig. 11. First claw level for structures with a width smaller than 20mm

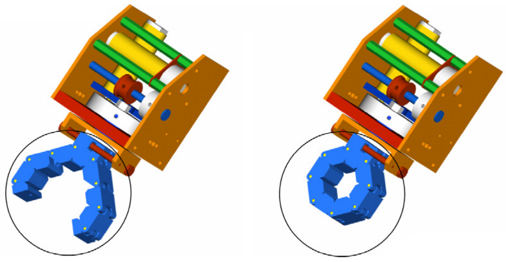

Fig. 12. Second claw level for structures with a width of 20mm to 60mm

VI. Control

A. *Overview of the electronics*

Each motor is controlled by a motor control module including power electronics, inputs for encoders and a microcontroller which commands the motor either in speed or position. All motor modules are connected to another module, the master module, which translates the commands received from the control interface to the motor modules. The modules are linked by a four-wire cable providing power supply (0V and 12V) and a I^2C Bus (serial clock and serial data). The high level manipulation of the robot is made with a gamepad through a control interface.

B. *Remote control*

There are different ways to control mobile robots, ranging from totally remote-controlled to completely autonomous. Considering the targeted application of the robot, namely to search victims in collapsed buildings, an autonomous robot would be preferable. However, it would require a sophisticated and complex control architecture and several sensors to control the seven degrees-of-freedom of the robot effectively. In this first step of the project, MATE-1 will be remote-controlled and manipulated with a gamepad. Thus no sensors are needed and the electronic circuits are simpler.

The gamepad allows for the remote control of MATE-1. The functions of the available buttons and axes have been chosen carefully in order to offer an easy and intuitive manipulation of the robot. To facilitate its control further, the movements induced by the different actuators are totally decoupled and each motor is controlled by its own buttons and axes. The basic idea for the manipulation of the robot is to define a fixed and a mobile gripper. Once the fixed gripper has been selected, the mobile gripper will move in a coordinate system fixed in point C as shown in Figure 13. The coordinates which describe the position of the mobile gripper are chosen as follow:

- α : Angle between the two thighs which is controlled by the motor M1.
- β : Angle between the fixed gripper and the first thigh. This angle is defined by the motor M2 corresponding to the fixed gripper.
- γ : Angle between the second thigh and the mobile gripper. This coordinate is steered by the motor M2 corresponding to the mobile gripper.
- ϕ : Angle which determines the orientation of the robot in regard to the fixed gripper. This angle is controlled by the motor M3 corresponding to the fixed gripper.
- θ : Angle which determines the orientation of the mobile gripper. This angle is steered by the motor M3 corresponding to the mobile gripper.

VII. Performance evaluations

In order to test the robot's capabilities, some experiments have been carried out. These experiments give an idea of the aptitude of the robot to use its different modes of locomotion.

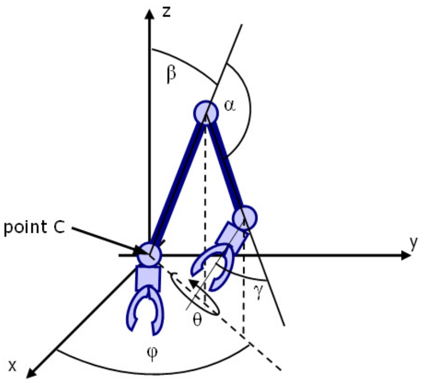

Fig. 13. Coordinates which define the position of the mobile gripper

A. *The robot's ability to grip*

Since the hold of the robot during locomotion is of prime importance, the first analyse was devoted to studying the robot's ability to grip. Several experiments showed that the robot is capable to grip structures with a width up to 60mm. However, the grip is not strong enough for the robot to be able to lift its own weight in any position due to a suboptimal desing of one part of the claws. Once this problem has been solved, further experiments will provide a exhaustive characterisation of the robot's ability to grip.

B. *Locomotion on flat surfaces*

The use of wheg-mode for locomotion on flat surfaces was tested with the three experiments described below.

Wheg-mode: The first experiment was intended to test the robot's ability to move in wheg-mode. The robot had to cover a distance of 2m without tilting. If the robot was able to do so, the experiment was successful. The experiment was repeated ten times for two different orientations of the gripper-heads (Figures 14 and 15). The results of the analysis are represented in table I. If using wheg-mode for locomotion, the risk of tilting is the highest when the robot stands on its two claws. Therefore, this situation should be avoided. Nevertheless, it was encountered during the experiments. Whereas the robot tilted in such a situation if it had its gripper-head oriented according to 14, it did not topple if the gripper-head was oriented as shown in Figure 15. Hence, the risk of tilting is smaller with a gripper-head oriented according to 15. After tilting, the rotation of the grippers around the axis a_{M2_A} and a_{M2_B} respectively was sufficient to set upright the robot again.

Wheg-turn-mode: The second experiment tested the robot's capability of changing direction in wheg-mode. Hence, the robot should turn as much as possible using the rotation of its claws (M3_A and M3_B). Ten tests showed that the robot is can easily change it's direction on flat surfaces by using the rotation of its gripper-heads. For an efficient turning, the robot has to be to-

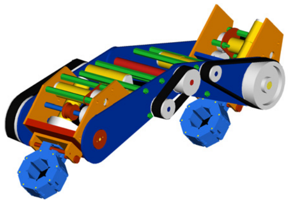

Fig. 14. First orientation of the gripper

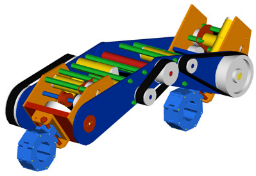

Fig. 15. Second orientation of the gripper

tally outstreched and it's claws have to be closed. The robot's angle of rotation is then unlimited.

Wheg-mode in grassy terrain: The last experiment on the robot's ability to move in wheg-mode tested its capability to use it in grassy terrain. As for the first experiment on wheg-mode, the robot had do cover a distance of 2m without tilting. If the robot was able to do so, the experiment was successful. The results of this tests (table I) show that the risk of tilting is much higher if the surface is not flat. Hence, the robot cannot move as fast on grassy terrain as it moves on flat surfaces. The robot's speed on flat surfaces is around 6cm/s and is four times higher than the robot's speed on grassy terrain.

TABLE I
LOCOMOTION ON FLAT SURFACES

Experiment	**Number of successful experiments**
Flat surface, 1st gripper orientation	
Flat surface, 2nd gripper orientation	
Grassy terrain, 2nd gripper orientation	

VIII. CONCLUSION

The design, implementation and evaluation of a small biped robot for all-terrain applications have been presented. A subtle design of it's mechanical structure allowed combining different locomotion concepts without additional components (parts or actuators). Hence, the robot can use different modes for locomotion, depending on the terrain it is facing: Whereas in complex rough terrain, the robot will move by gripping on adequate shapes, it will use it's grippers as whegs on flat surfaces.

Some experiments have been made to test the robot's capabilities. They show, that the robot is indeed able to use wheg-mode for locomotion on flat and mostly flat surfaces. The ability of the robot to grip different shapes could not be analysed yet due to a suboptimal design of one part of the claws. Hence, the robot is not able to grip strong enough to lift its own weight in any position. Once this problem has been solved, further experiments will provide a exhaustive characterisation of the robot's different modes of locomotion.

In future research, the control of the robot should be improved. For instance, the robot could have some pre-programmed basic behaviors to facilitate its remote control. The robot's overall behavior (choice of direction or mode of locomotion) would then still be remote-controlled by its manipulator, but the local adaptation to the ground structure would be automated.

Although several modifications have to be done to develop an efficient system, the locomotion concept of MATE-1 seems to be a promising solution for an all-terrain robot.

IX. ACKNOWLEDGEMENTS

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