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# Development and Control of a Buggy Robot for Operations on Unstructured Terrain

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## Abstract

*The demand for mobile robots for hazardous field tasks, such as rescue operations in disaster scenes or landmine detection and removal has been increasing in recent years. Since electrical infrastructure is seldom available in such situations, robots that rely on chemical batteries or/and tethered connections to external electric generators suffer severe limitations in operation time and mobility. A different approach is being sought in this research, which involves the use of a combustion engine for on-board electric generation. For practical purposes, the authors used a commercial 4-wheel buggy as the base platform. Some mechanical adaptations in the steering, throttle, gearshift and brake mechanisms were performed, and the developed mobile platform (Gryphon-I) can be computer controlled. This paper introduces new strategies for the control of Gryphon-I over uneven terrain, and the effectiveness of the proposed methods is evaluated experimentally.*

## 1. Introduction

Field tasks are among the most promising and practical applications for robotic systems. Actually, immediate automation is required in several hazardous field tasks that are currently performed by human workers. Search and rescue operations in disaster scenes (Figure 1) and landmine detection and removal are only a few examples. Several researchers have been dedicating great efforts to develop mobile robots that can be useful in such situations [1]-[3]. Nevertheless, one detail is usually overlooked: **the energy source**.

The majority of the current robotic systems depend on chemical batteries or tethers connected to external power sources to receive electric energy. In either case, proper infrastructure is required in the site of operation to recharge the batteries or to control the energy tethers. However, electrical infrastructure cannot be expected at the time and places these robots are supposed to operate, such as in disaster-stricken areas or in landmine fields (Figure 2). Hence, an external electric power supply is usually required. The traditional solutions to the problem of energy involve frequent interruptions for recharging batteries or maneuvering tethers, restricting the mobility and the operating time of the system.

***Figure 1:*** *Disaster zone after an earthquake*

The objective of this research is to implement a robotic system able to operate uninterruptedly for long periods of time and without human assistance in such environments. One possible solution is the use of a mobile platform driven by a combustion engine [4]. The engine can be used to drive the system and also for electricity generation. Combustion engines, in spite of low efficiency, still present much higher energy densities per mass and volume when compared to traditional chemical batteries [5].

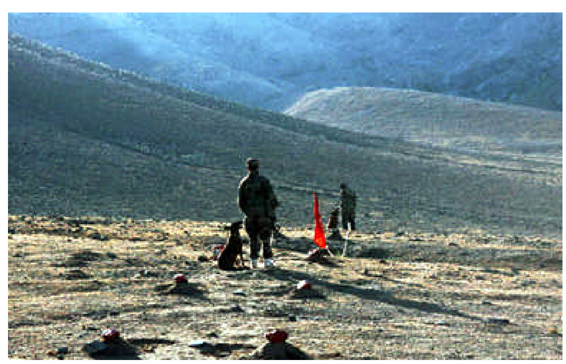


***Figure 2:*** *Landmine field in a remote area*

This research also considers the advantages of using hyper-tether [6] connection in order to transmit the electrical energy generated by the combustion engine of the developed mobile platform to other electrical robots and tools. An example of application, the far-reach tethered working tool, is illustrated in Figure 3. The developed platform (Gryphon-I), on the right, works in coordination with another electrical mobile robot, both being connected by hyper-tether to a suspended tool. The tool can be moved between the two bases, scanning the ground without touching it, while both platforms move forward slowly, with controlled displacements. In addition, Gryphon-I can provide electric energy to the other mobile robot by the hyper-tether connection, so that both robots operate continuously for long periods of time. This configuration is especially useful for the implementation of autonomous landmine detection systems in remote areas.

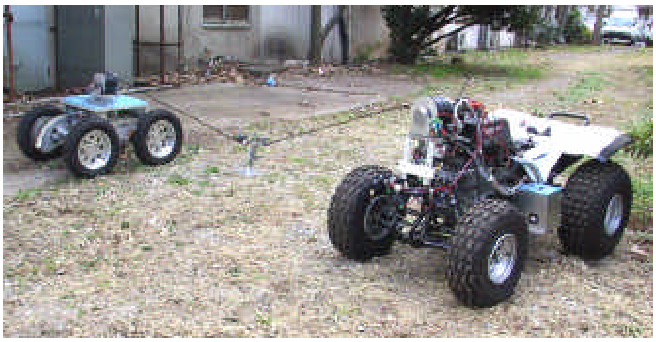


***Figure 3:*** *Example of landmine detection system using hyper-tether concept*

In this paper, the development of speed and displacement control of Gryphon-I on flat surfaces will be discussed. In addition, motion control on slopes, necessary for applications in fields and on uneven terrain, will also be addressed.

## 2. Gryphon-I

In order to solve the problem of limited energy for field systems, a robot equipped with energy generation capability is being sought in this research. As mentioned before, the combustion engine is one of the most suitable solutions for practical and immediate applications. Construction vehicles, such as bulldozers and trucks, could be used for that purpose, but they cannot be employed in narrow spaces to perform delicate tasks, such as landmine detection, due to their large dimensions. Another option would be to equip a conventional electric actuated robot with a combustion engine for electricity generation, but this would require high payload capacity, and the weight of the engine could deteriorate the mobility of the robot.

On the other hand, a combustion engine driven mobile robot could solve the problems of payload and mobility, but at the cost of long development time and very high expenses. However, the hazardous field tasks mentioned before require **immediate** automation. In addition, a **practical** system should be affordable, based on standard components.

Therefore, we decided to modify a commercially available buggy and convert it into a fully automatic machine (Gryphon-I), with mechanisms for steering, gear-changing, acceleration and braking, as shown in Figure 4. The details of the mechanical modifications can be seen in [4].

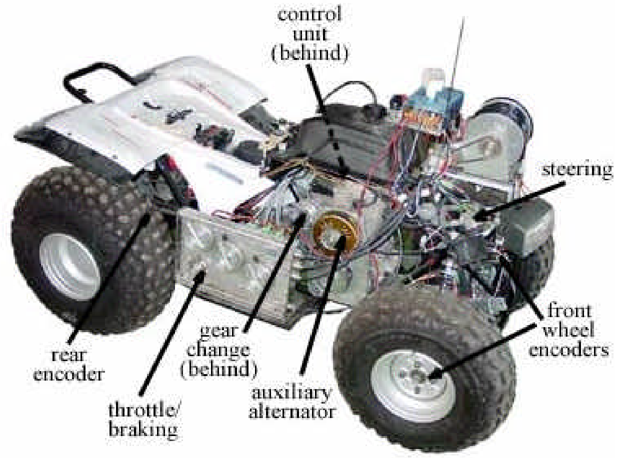



***Figure 4:*** *Gryphon-I and its modifications*

Furthermore, Gryphon-I is also equipped with an auxiliary, external alternator that generates up to 500W of electric energy. This energy can be used by the mechanisms assembled on Gryphon-I and can also be distributed or transmitted to other machines or robots working cooperatively through the hyper-tether connection.

## 3. Control and Experiments

Acceleration, braking and steering control on paved surfaces has already been discussed in detail in [4]. The speed control of Gryphon-I has also been discussed in [4], but it will be described in more details in this paper. Furthermore, displacement control and motion control on slopes will also be addressed.

### 3.1. Speed Control

Initially, the throttle and brake commands were actuated direct and independently by radio control, in order to test several different patterns and verify which combination would provide the best results to keep constant speeds. When trying to accelerate the buggy while keeping the brakes actuated, the speed would oscillate, as shown in the left part of Figure 5. Even after releasing completely the brakes, in the right part of Figure 5, it was difficult to keep constant speeds with only the “direct” throttle control. Nevertheless, this initial phase of experiments provided valuable information regarding the behavior of the buggy with different acceleration and braking patterns.

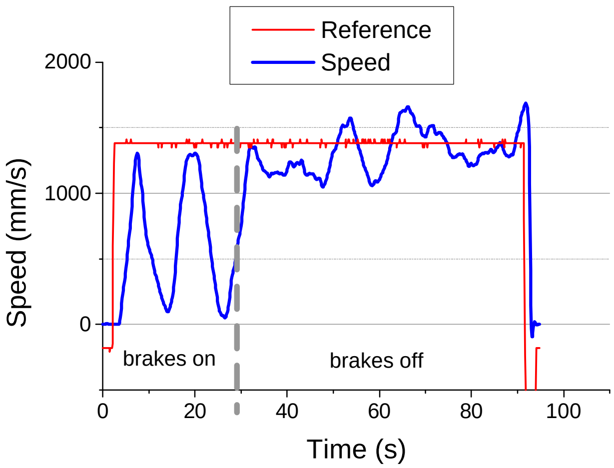



***Figure 5:*** *Speed during “direct” control experiments*

The rules of actuation on brakes and throttle cable were implemented, and a digital PID controller was explored as a possible speed controller for Gryphon-I. However, there were delays – mostly in the combustion engine and in the continuously variable transmission – that made the integral component of the PID controller accumulate errors. As a result, during experiments on flat surfaces, the command values caused the speed of the vehicle to oscillate around the reference value, with overshooting values of as much as 50% of the reference speed.

The speed tended to stabilize around the reference value when the gain of the integral component was reduced. However, even without the integral component (PD controller), the combustion engine still showed delays when accelerating, as can be seen in Figure 6. According to the results of the initial phase of experiments, when the throttle cable was driven directly by remote control, those delays would decrease if the engine were kept slightly accelerated. To keep the engine of Gryphon-I always slightly accelerated without increasing its speed, an on-off component was included in the speed control strategy. The output of the on-off component was added to the command signal generated by the PD controller, with frequency of 1Hz and amplitude varying according to the speed of the buggy, as seen in Figure 7 – for higher speeds, the amplitude of the on-off block would be reduced, since the need for keeping the engine accelerated would also decrease.

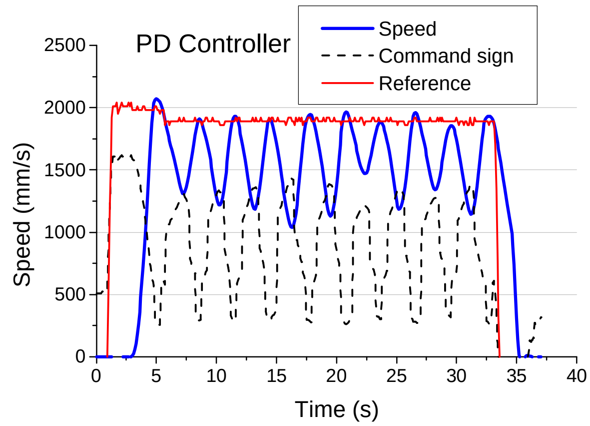



***Figure 6:*** *Speed experiments with PD controller*

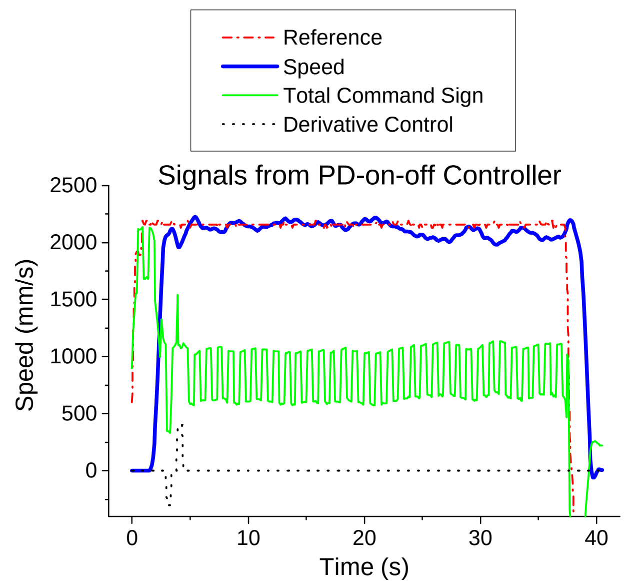



***Figure 7:*** *Speed and command signals with PD-On-Off controller*

The physical meaning of this on-off component is the oscillation of the throttle cable in small amplitudes. This results in an oscillation in the aperture of the throttle valve, enough to increase the rotation speed of the engine, but not enough to accelerate the vehicle due to delays and losses in the clutch and in the variable transmission. Therefore, the engine is kept in a state of “readiness”, and responds much faster to any small variation in the non-oscillating signal of the PD controller.

According to the results of Figure 7, the derivative control was necessary only in the beginning, when Gryphon-I was accelerating. The total command signal is the composition of the PD and on-off blocks. In addition, the speed of Gryphon-I was kept very close to the reference value, with variations inferior to 5% when running on tarmac.

### 3.2. Displacement Control

For autonomous locomotion in field applications, attitude and navigation sensors can be used to calculate the position of the vehicle. However, some applications require that the buggy perform small displacements (of the order of tens of centimeters), such as the far-reach tethered working tool shown in Figure 3. In those cases, the encoders assembled on the wheels of Gryphon-I could provide enough information to ensure the positioning of the vehicle. This is a dead-reckoning strategy, and therefore it should not be used for large displacements or for navigation purposes.

In order to implement displacement control, the speed registered by each wheel encoder is integrated and combined to calculate an average distance. The average distance is compared with the displacement reference, and this generates error signals that actuate on the throttle and brakes of Gryphon-I, as shown in the block diagram of Figure 8.

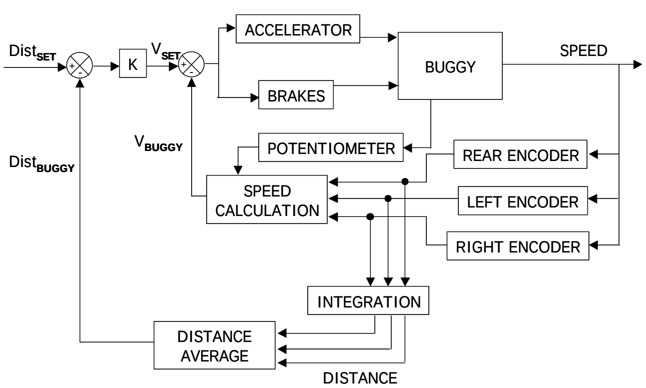



***Figure 8:*** *Block diagram of displacement control*

The rules and gains of the displacement control (e.g. when the vehicle stops to accelerate; how intensely the brakes are applied) had to be calibrated experimentally. The results of experiments performed on tarmac are displayed in Figure 9, and demonstrate that Gryphon-I executed controlled displacements of 1m, 2m and 5m, forward and backward, with positioning discrepancies inferior to 4%.

### 3.3. Motion control on slopes

With the results discussed until here, it is possible to control speed and displacement of Gryphon-I on flat surfaces. Nevertheless, in field applications, slopes and irregular terrain are quite common features.

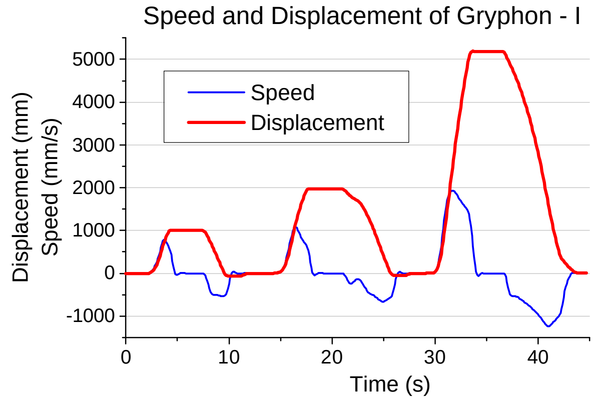



***Figure 9:*** *Displacement control experiments*

As one can expect, the rules of acceleration and braking change when the vehicle is on a slope. The actuation on the brakes is stronger to ensure that the buggy will not move when stopping in the middle of a slope. The aperture of the throttle valve also increases, to amplify the output power of the combustion engine when moving uphill. Furthermore, when resuming to climb a slope, coordinated actuation of brakes and throttle is important to avoid accidental retrocedings.

In order to change properly the acceleration rules, an attitude sensor was used to measure the pitch and roll angles of Gryphon-I as it moves over uneven terrain. The attitude sensor was implemented with accelerometers, using the gravity as a reference, and thus avoiding problems with integration errors and drift. The output of the accelerometers, however, would be influenced by the vibration of the combustion engine and also by the acceleration of the own vehicle. These effects were compensated by software, with filters that inhibit any oscillations in the accelerometer output that might be caused by strong variations of speed of the buggy. The filtered signal of the accelerometers, representing only the pitch angle of Gryphon-I as it moves through slopes, is shown in Figure 10.

When moving on uneven terrain, the roll position might affect the pitch signal. That is why the attitude sensor measures both pitch and roll angles. When the roll angle is significant, it can be used to correct the pitch angle registered by the attitude sensor.

The behavior of Gryphon-I with the modified acceleration rules was verified during experiments performed on an 8-degree paved slope. Results of experiments, presented in Figures 11 and 12, show that Gryphon-I, initially parked on the slope and without the modified rules for slopes, returned almost 1 meter when trying to stop in the reference point, and then retroceded again when continuing to climb the slope. With the modified rules for slopes, however, Gryphon-I was able to stop at the reference point and to start moving on the slope without retroceding. The curve named "attitude sensor" in Figures 11 and 12 is the output of the pitch axis of the attitude sensor assembled on the vehicle, and is registering the inclination of 8 degrees of the slope.

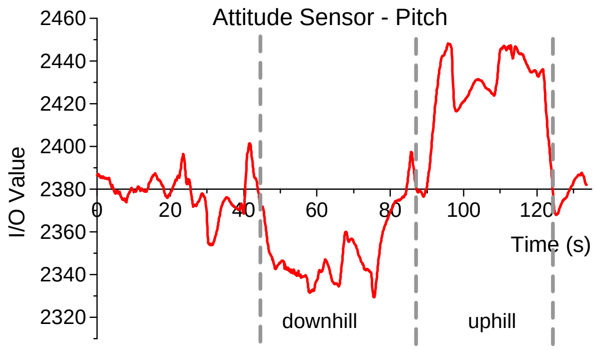



***Figure 10:*** *Pitch output of attitude sensor in experiments on slopes (filtered signal)*

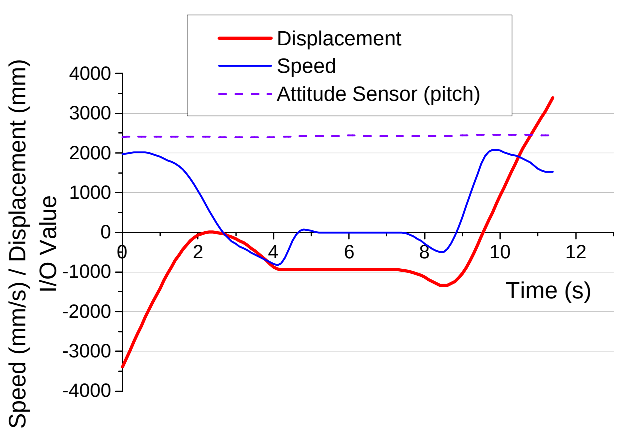



***Figure 11:*** *Position and speed of Gryphon-I on an 8-degree-slope with motion rules for flat terrain*

Figure 13 shows sequences of pictures taken from the above-mentioned experiments. In column (a), Gryphon-I is using the acceleration rules for flat surfaces, and moves almost 1 meter backward before it really starts to climb the slope. In column (b), this problem is avoided by employing the special rules of acceleration for slopes.

These results validated the rules for control of a combustion engine powered vehicle on flat surfaces and also on slopes.

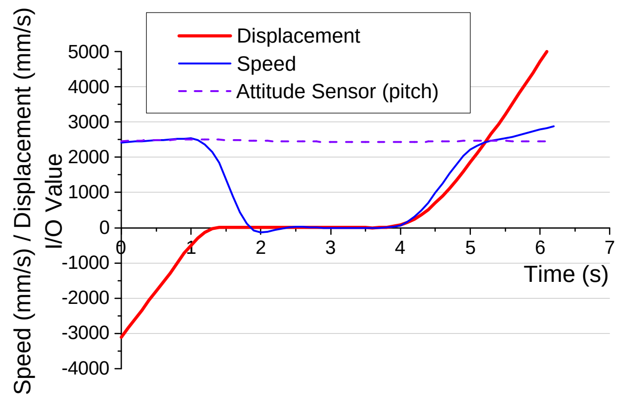



***Figure 12:*** *Position and speed of Gryphon-I on an 8-degree-slope with special motion rules for slopes*

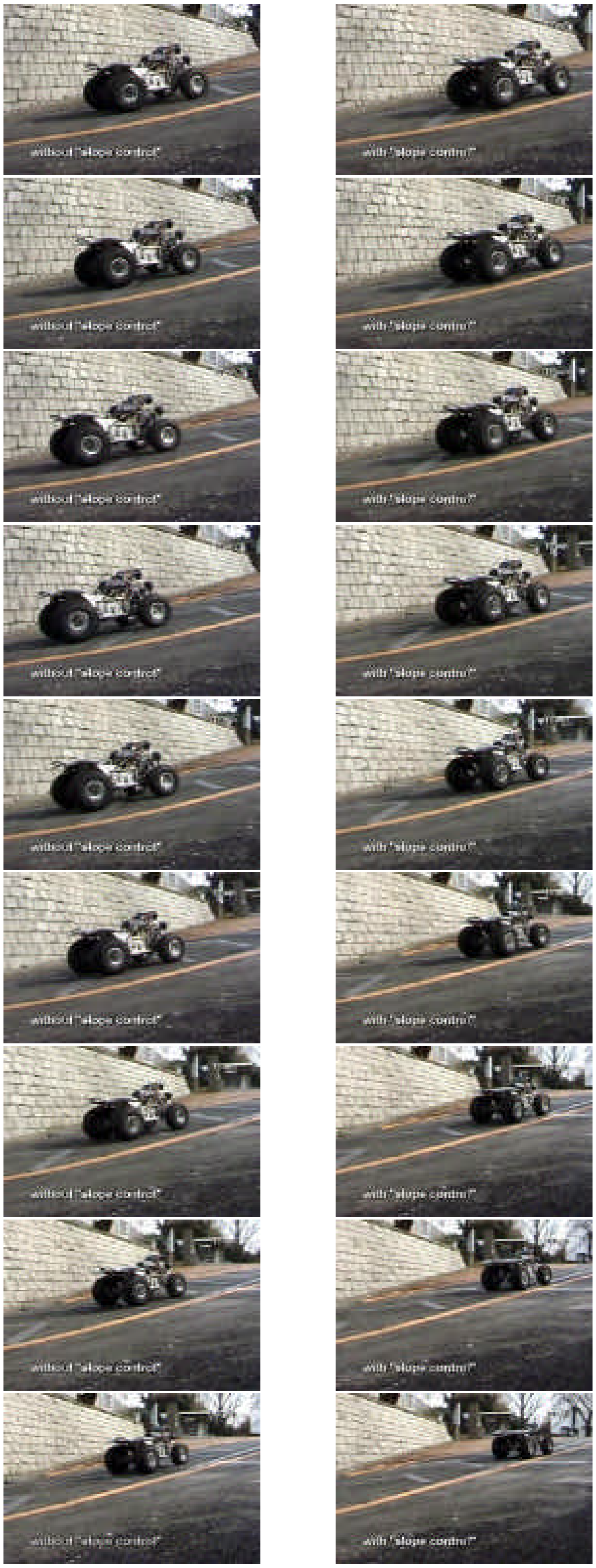
## 4. Conclusions and Future Steps

After identifying the need for a robust mobile platform for operation in fields and other locations deprived from basic infrastructure, an off-road buggy equipped with a combustion engine was converted into an automatic vehicle controlled by computer. With an alternator linked to the combustion engine, the modified buggy (Gryphon-I) can generate electric energy and transmit it to other robots and tools in remote areas using hyper-tether connection.

The basic control of Gryphon-I was developed with several experiments performed on flat surfaces and on slopes. Even when operating on slopes, Gryphon-I was able to move in a safe and stable way, with controlled velocity. Furthermore, the results of experiments on displacement control were presented, and an application that requires such control (landmine detection with the "far-reach tethered working tool") was also briefly introduced.

From now on, the use of other sensors with Gryphon-I will be considered (including laser range finder and video cameras), culminating with the fusion of the information provided by all sensors and development of autonomous navigation capability.

Furthermore, the applications described in this paper will be implemented and their performances will be evaluated in outdoor environments, simulating the conditions of fields and other remote, uneven terrain.




*(a)* *(b)*

***Figure 13:*** *Sequence of photos taken from experiments on an 8-degree slope: (a) without and (b) with special acceleration rules for slopes*

## 5. Acknowledgements

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