Variable Geometry Tracked Vehicle, description, model and behavior

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***Abstract*— This paper presents a prototype of tracked UGV (Unmanned Grounded Vehicles) called B2P2. This tele-operated robot has been designed to intervene in unstructured environments like for example battlefield or after an earthquake. This robot based on an original system of multiple articulations can be classified into the VGTV (Variable Geometry Tracked Vehicle) category. The proposed concept allows the robot to adapt its shape in order to increase its clearing capability. Unlike existing robots, the tension of the caterpillars is actively controlled and can be turned off to increase the robot/ground contact surface needed for some special kind of obstacles. After a short state of the art, the paper presents the detailed architecture of the robot. The third part introduces the geometric model of the robot followed by the control algorithm used to tense or release the caterpillars. The behavior of the robot over several obstacles (staircase, curb and bumper) is analyzed and the necessity of releasing the tracks is discussed.**

I. INTRODUCTION

The use of robots in dangerous environment like partially collapsed buildings or nuclear power station is currently a research topic of prime interest. Designing generic robots well suited to a large variety of missions and environments is still challenging : the challenge is thus to design the smallest robot as possible (able to pass into narrow openings) and with the best clearing capabilities. The prototype called B2P2 presented in this paper is a tracked vehicle based on an actuated chassis (Fig. 1). It has been designed to maximize the clearing capability to size ratio. Unlike existing robots the track's tension can be controlled on our prototype. Experiments presented in the following will discussed of the interest of controlling the track's tension. This article is organized as follows. Section 2 presents an overview about a selection of existing robots. Section 3 gives the technical description of our prototype. Next section is dedicated to the models and to the controller used to actuate the chassis. Section 5 discusses about real experiments performed with the robot over three obstacles : a curb, a staircase and a bumper. A general conclusion ends the paper and presents some perspectives.

II. EXISTING UGVS

A. Wheeled and tracked vehicles with fixed shape

This category gathers non variable geometry robots. Theoretically, this kind of vehicles are able to climb a maximum step twice less high than their wheel diameter. Therefore their dimensions are quite important to ensure a large clearing capability. Probably, this conception presents a high reliability [1] but those robots cannot be used safely in unstructured environments like after an earthquake [2].

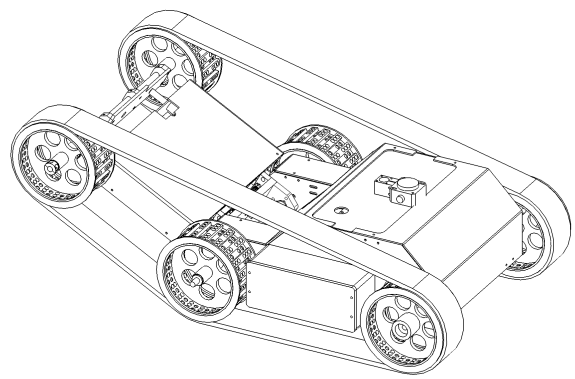


Fig. 1. B2P2 prototype

Fig. 2(a) and 2(b) present two vehicles dedicated to reconnaissance and surveillance.

B. Variable Geometry Tracked Vehicle

A solution to ensure a large clearing capability and reduced dimensions consists in developing tracked vehicles which are able to modify their geometry in order to move their center of mass and climb higher obstacles than their wheel diameters. The Micro VGTV Fig. 3(a) is a good example of the possibility of this kind of UGVs. Indeed, with a wheel diameter of only 6.5 cm, it is able to climb a step of 25 cm. [3] provides endurance tests results for this UGV.
Another solution consists in using flippers as the Packbot (Fig. 3(b)). This kind of VGTV can clear a lot of different obstacles and its control is easy, but it does not offer a gentle clearing as the caterpillars' models. For more information and a detailed survey on clearing capability of the packbot, the reader can consult [4].

Our prototype (Fig. 1) belongs to this category and can clear a maximum step of 35 cm high with a wheel diameter of 12 cm.

(a) ATRV-Jr robot. Photo Courtesy of AASS, Örebro University.

(b) Talon-Hazmat robot (Manufacturer : Foster-Miller)

Fig. 2. Two UGV with fixed shape models

(a) Micro VGTV (Variable Geometry Tracked Vehicule manufacturer: Inuktun Ltd). Photo courtesy of Inuktun Services Ltd.

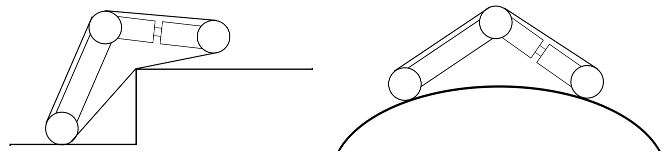
(b) Packbot (manufacturer: IRobot)

Fig. 3. Two VGTV models

III. Description of B2P2

A. Mechanical description

Our conception is based on a similar system as the Micro VGTV (Fig . 3(a)) previously cited. A revolute joint coupled with a translation system situated on the robot allows it to change its shape (Fig. 4) keeping the caterpillars tense. This system, contrary to the one used on the Micro VGTV is actively controlled. Fig. 5 shows an illustration of configurations, on (a), by releasing the tracks it becomes possible to move the center of gravity (CoG), and on (b), the robot morphology is adapted to the ground.



a) b)

Fig. 5. Different configuration of B2P2 on obstacles. In a), the caterpillars are tense, and in b), they are not to increase the contact surface. Note that even if the system is turn on, the caterpillars are not hardly tense ; it allows soft mass transfer and clearing

Because of this active system, B2P2 is equipped with four motors :

- Two motors are dedicated to the rear wheels rotation (tracks actuators).
- One motor actuates the rotational joint
- One motor actuates a driving screw to control the distance between the second and the third axle (i.e. the tightness of the tracks).

B. Embedded computation and sensors

The robot is equipped with multiple sensors, on-board/command systems and wireless communication systems.

- Onboard command systems :
  - PC104 equipped with a Linux system compiled specifically for the robot needs based on a LFS.
  - An home-made I2C/PC104 interface.
  - Four integrated motor command boards running with RS232 serial ports.
  - Four polymer batteries which allow more than one hour of autonomy.
- Sensors :
  - An analogic camera for tele-operation.
  - A GPS to locate the robot in outdoor environments.
  - A compass.
  - An 2-axis inclination sensor (roll and pitch).
- Wireless communication systems :
  - An analog video transmitter.
  - A bidirectional data transmitter.

IV. B2P2's model and control

A topically problem with VGTVs is to determinate the position of the CoG because it is not fixed. The control of this CoG can be a real asset to overcome obstacles and a model of the robot is essential. In this section, the geometric model ([5], [6] and [7]) is first described and the position of the CoG is deduced from the model.

A. Geometric model

The geometric model is used to define the robot's relative position in a general frame. Thus, it is possible to formulate the CoG in terms of the elements and position of the UGV (the tracks' weight is negligible in regard to the robot's weight).

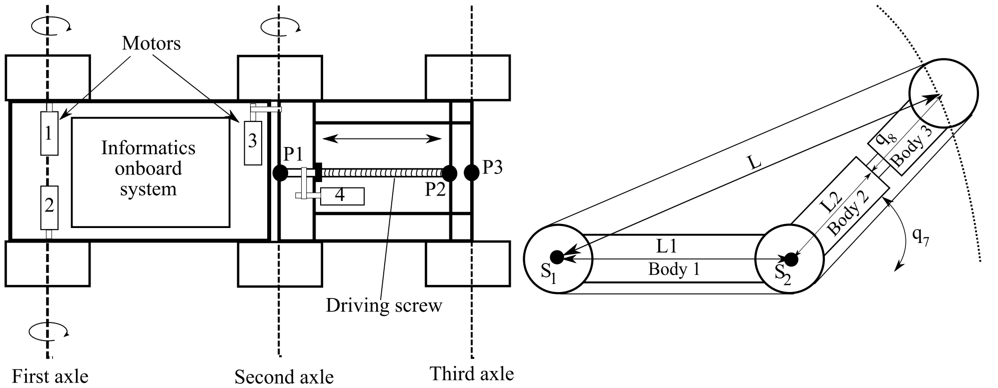


Fig. 4. Overview of the B2P2 mechanical structure.

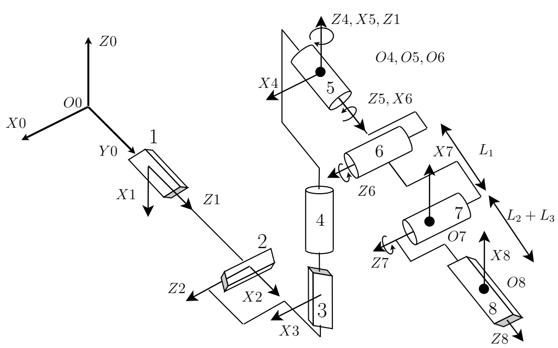


Fig. 6. B2P2's geometric model. The robot is decomposed into three segments. The first is situated between joints 6 and 7, the second starts at the joint 7 and the third at the joint 8. L_1, L_2 and L_3 represent respectively the length of the segments 1, 2 and 3.

j	σ_j	α_j	d_j	θ_j	r_j
1	1	$\frac{-\pi}{2}$	0	$\frac{\pi}{2}$	q_1
2	1	$\frac{\pi}{2}$	0	$\frac{\pi}{2}$	q_2
3	1	$\frac{-\pi}{2}$	0	$\frac{-\pi}{2}$	q_3
4	0	0	0	q_4	0
5	0	$\frac{-\pi}{2}$	0	$q_5 - \frac{\pi}{2}$	0
6	0	$\frac{-\pi}{2}$	0	$q_6 - \frac{\pi}{2}$	0
7	0	0	L_1	$q_7 + \frac{\pi}{2}$	0
8	1	$\frac{\pi}{2}$	0	0	$L_2 + q_8$

TABLE I
PARAMETERS OF DENAVIT-HARTENBERG

First the robot shape has to be decomposed as it is shown on Fig. 6. Joints 1 to 6 describe the position and the orientation of the robot in the environment. Joints 7 and 8 represent the two actuated joints described in section III-A.

B. Denavit & Hartenberg description

From the Fig. 6, the Denavit & Hartenberg (DH) formulation allows the computation of several parameters (table I) which are used to compute transport matrix in order to formulate the coordinates of a point in any frame of the model described by the vector q of the 8 joints variables :

$$q = [q_1, q_2, q_3, q_4, q_5, q_6, q_7, q_8]^T$$

where q_i represents the articular value of the i_{th} joint. For practical purposes the position (q_1, q_2 and q_3) is computed thanks to a GPS, the orientation (q_4) by using a compass, the ground shape (q_5 and q_6) by using an inclination sensor and the two last parameters (q_7 and q_8) are given by the motors 3 and 4 encoders values.

Thanks to these parameters, it is possible to formulate the position of the CoG of each segment in the frame R_0 whatever the position of the different elements of the robot.

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{R_0} = \frac{m_1 T_6 \begin{bmatrix} z_1 \\ x_1 \\ y_1 \\ 1 \end{bmatrix}_{R_6} + m_2 T_7 \begin{bmatrix} z_2 \\ -y_2 \\ x_2 \\ 1 \end{bmatrix}_{R_7} + m_3 T_8 \begin{bmatrix} -y_3 \\ z_3 \\ x_3 \\ 1 \end{bmatrix}_{R_8}}{m_1 + m_2 + m_3} \tag{1}$$

where x_i, y_i and z_i are the coordinates of the CoG of the i^{th} element of the robot, T_j represents the transport matrix from R_j to R_0, and m_i represents the weight of the i^{th} element of the robot.

C. Controller

As its shown on Fig. 4 the tension of the tracks is maintained by modify the length between the third and the second axle i.e. q_8. The trajectory of the third axle is given by an ellipse defined by two seats (S_1 and S_2) located on the first and the second axles :

$$L + L_2 + q_8 = K \tag{2}$$

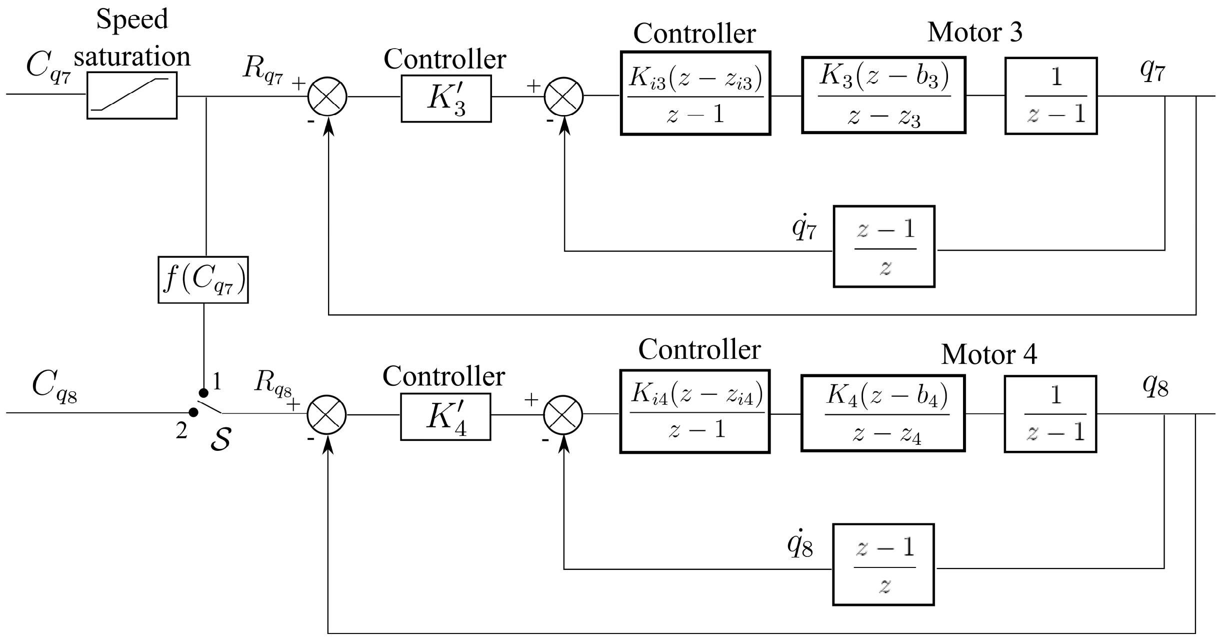


Fig. 7. Elevation/translation control system

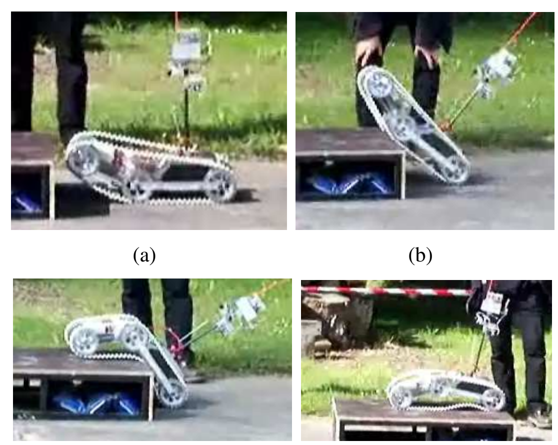
where L, L_2 and q_8 are referenced on Fig. 4. K is a constant parameter depending on the length of the caterpillars. To achieve the previous equation, q_8 is function of q_7 and must evolve as follow :

$$q_8 = f(q_7) = \frac{L_1^2 - K^2}{2(L_1 cos(\pi - \mid q_7 \mid) - K)} - L_2 \qquad (3)$$

Practically, the system has to react accurately to an elevation command, so a position/speed control system was computed. Fig. 7 presents the controller architecture of the elevation system. Motor 3 drives the revolute joint (q_7) and motor 4 drives the prismatic joint (q_8). Speed and position of both motors are closed loop controlled, $K_4, b_4, z_4, K_3, b_3, z_3$ are the electromechanical parameters of motors 4 and 3 respectively. $K'_3, K_{i3}, z_{i3}, K'_4, K_{i4}$ and z_{i4} are the controller parameters associated to each motor. R_{q_7} is the angular reference input and R_{q_8} is the linear position reference input. A software switch ($\mathcal{S}$) allows to choose the running mode. In position 2, R_{q_7} and R_{q_8} are independent and linked to C_{q_7} and C_{q_8} which are the command coming from the human pilot. In position 1, R_{q_8} is linked to C_{q_7} through equation (3). In both case, a speed saturation of C_{q_7} is added to avoid brutal variation of the reference inputs.

V. Experiments

In this section, several approaches of different obstacles will be illustrated by explaining pictures derived from a trial day and an experiment made in our laboratory.



(a) (b) (c) (d)

Fig. 8. The clearing of the curb

A. Curb

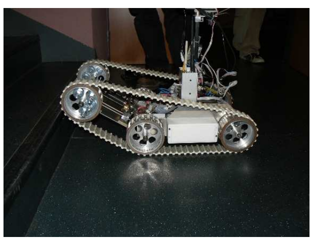
During a trial day organized by the French army in 2006, our prototype had to pass through a curb of 35 cm riser ; it is certainly its maximum obstacle height. It was tele-operated. The visual feedback was provided to the tele-operator thanks to a video transmitter fixed on the top of the mast visible on Fig. 8. This clearing can be divided into two stages :

- The approach of the curb (Fig. 8(a) and 8(b)).
- The clearing of the curb (Fig. 8(c) and 8(d)).

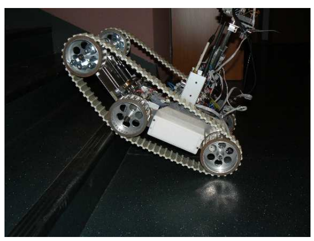
1) The approach of the curb: Fig. 8 describes the different steps of this approach. First, the robot is approaching while moving up the front part. Then, when the curb is reached the robot's pitch is rising up until the second axle reaches the curb. At this moment (Fig 8(b)), the stability limit is reached, indeed, if the pitch increases a little more, B2P2 is going to fall. Keep clearing without falling is the goal of the second step of the clearing.

2) The clearing of the curb: In order to increase the contact surface, the caterpillars was released by turning off the translation system. This "trick" increases the clearing capability but the caterpillars can slide out of the wheels, so the piloting has to be very accurate. Fig. 8(c) illustrates this step : the robot is going forward slowly while moving down the front part. The difficulty increases with the curb's height. This is a delicate step because the prototype is in a stability limit configuration and the pilot ability makes the clearing possible. However, the knowledge of the position of the CoG and the ground shape could be used to compute an assistance steering for this kind of obstacles.

B. Staircase



(a)



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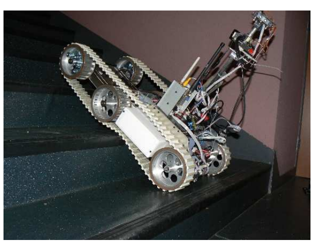
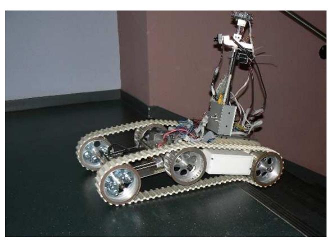


(c)



(d)

Fig. 9. Clearing of a staircase : pictures

The pictures presented here are derived from an experiment performed in our laboratory. The prototype reached a staircase sets of 15 cm risers and 28 cm runs with its caterpillars tense. It can be decomposed into three parts :

- The clearing of the first step (Fig. 9(a) and 9(b)).
- The clearing of the middle steps (Fig. 9(c)).
- The clearing of the final step (Fig. 9(d)).

Fig. 10 illustrates those steps. Note that the clearing of the first step and the clearing of the final step are done respectively as the first and second steps of the clearing of the curb.
After clearing the first step the robot is in the position noticed on Fig. 9(b) and then it climbs naturally the stairs by moving forward (Fig. 9(c)). At each step, it is gently swaying when the CoG is passing over the step (Fig. 10(f)). This oscillation is dependant on the ratio between the size of the robot and the size of the steps. Of course, if the distance between two steps is longer than the robot length, the staircase is cleared like a succession of curbs.

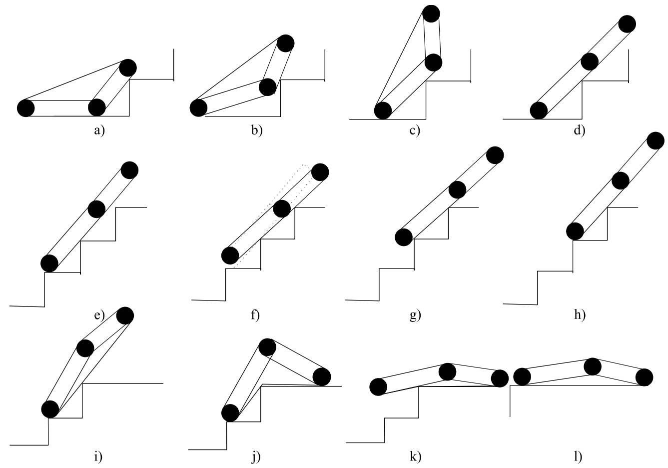


Fig. 10. Clearing of a staircase

C. Bumper

(a)

(b)

(c)

Fig. 11. Clearing of a bumper : pictures

Fig. 11 describes the clearing of a bumper of 25 cm height done in 2006 during a robotic trial day. First, the robot approaches the bumper as it was done with the previous obstacles. Once again, it is a critical step (Fig. 11(a)), because the prototype can fall if the bumper is too high.
Then, once the front part rose down there is no risk of falling anymore, and moving forward slowly makes the robot climb the bumper (Fig. 11(b)). Note that the caterpillars are not tense,

so the robot really takes on the obstacle shape in order to have the maximum adhesion. Thanks to this particularity, the clearing is easy and softly.
Finally, if the bumper is not too high, going forward makes the UGV clear. However the final step which corresponds to the reception on the ground could be dangerous for the mechanical structure of the robot if the pilot does not decreases the elevation angle before going forward as it is shown on Fig. 11(c).

VI. Conclusion

In this paper, an original prototype was described and validated by experiments. We detailed its behavior during the clearing of several obstacles. During all obstacle clearings, there is a critical step where the fall risk is important. Note that the robot model allow us to get the position of the center of mass, so with a known ground it becomes possible to prevent such risk and definitely avoid it. A longer time work could focus on computing a piloting assistance. Then, releasing the caterpillars before or during the clearing of an obstacle increases the risk of the tracks coming off but allow a soft and easy clearing of some obstacles. We can discuss about the purpose of that, because a little bigger VGTV equipped with flippers could reach same obstacles with the same facility and without a risk. However, the goal of our VGTV prototype was to develop a robot with reduced dimensions and important clearing capability.

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