Evolutionnary stair climbing controler for Unmanned Ground Vehicles

Jean-Luc PAILLAT Philippe LUCIDARME Laurent HARDOUIN

Laboratoire d'ingénierie des systèmes Automatisés (LISA) - Angers - FRANCE (e-mail: jlpaillat@gmail.com, philippe.lucidarme@istia.univ-angers.fr and laurent.hardouin@istia.univ-angers.fr)

Abstract: This paper presents a way to autonomously climb staircases with vehicles able to move their centre of gravity by changing their geometry. Grounded vehicles are categorised and a new architecture developed in our laboratory is described. After a survey about existing autonomous staircase clearing systems we propose a different approach based on a genetic training which control the adaptation of the robot to the ground during the climbing.

Keywords: Robot navigation, balance control, Genetic algorithms, Neural networks, Simulators.

1. INTRODUCTION

UNMANNED GROUND VEHICLE (UGV) is a topically research field applied to a wide range of applications like for example exploration or missions in hostile environments. Research laboratories and robotics companies are currently working on the design of tele-operated and autonomous robots. According to Casper and Murphy (2003) or Carlson and Murphy (2005) UGVs can be classified into three categories:

- Man-packable delineates the robots that can be carried by one man in backpacks.
- Man-portable delineates the robots that are too heavy to be easily carried by men, but small enough to be transported in a car or a HUMMV.
- Not man-portable delineates the robots that must be carried by a truck, a trailer or a crane.

This paper focus on the robots that belong to the man-packable category and more particularly the VGSTV (Variable Geometry Single Tracked Vehicles) as explain in the state of the art presented in the next section. Section 3 describes an original tracked vehicle based on an active tracks tension mechanism. Section 4 introduces previous works on autonomous staircase clearance. Section 5 discusses about stability and introduces the criteria used in the following of the paper that presents preliminary simulation results of autonomous controller.The proposed approach is based on artificial Neural Networks and evolutionary algorithms. A short conclusion ends the paper.

2. EXISTING UGVS

We already proposed in Paillat et al. (2008c) a categorisation of UGVs :

- Wheeled and tracked vehicles with fixed shape (Fig. 1),
- Variable Geometry Vehicles (Fig. 2),
  - · Tracked (Fig. 2(a) and (c)),
  - · Wheeled (Fig. 2)(b).
- Variable geometry single tracked robots .
  - · With not-deformable tracks (Fig. 3),
  - · With deformable tracks (Fig. 4).
- Self Reconfigurable robots (Fig 5).

Many commercial and experimental robots are described in the literature. Reader can consult Vincent and Trentini (2007), Misawa (1997), Clement and Villedieu (1987), Guarnieri et al. (2004) Kyun et al. (2005) or Ben-Tzvi and Goldenberg (2007).

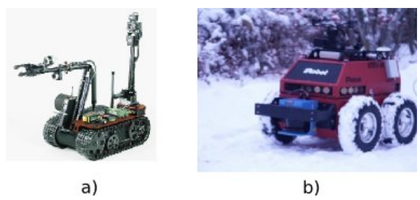

Fig. 1. a) : Talon-Hazmat robot (Manufacturer : Foster-Miller) b) : ATRV-Jr robot. Photo Courtesy of AASS, Örebro University

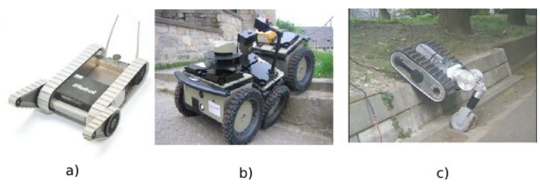

Fig. 2. a) : Packbot (manufacturer: IRobot), b) : RobuROC 6 (Manufacturer : Robosoft) c) : Helios VII

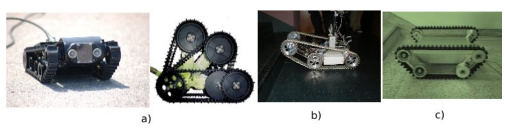

Fig. 3. a) : Micro VGTV (manufacturer: Inuktun Ltd) b) : B2P2 prototype c) : VGSTV mechanism

Note that each category have its own clearing capability and reliability. As example, a not variable geometry robot is theoretically, able to climb a maximum step twice less high than its wheel diameter. Obviously, important dimensions are necessary to ensure a large clearing capability. This conception probably presents a high reliability but those robots cannot be

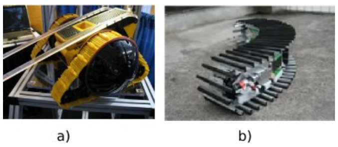

Fig. 4. a) : Viper robot (Manufacturer : Galileo) b) : Rescue mobile track WORMY

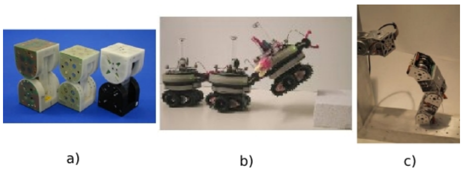

Fig. 5. a) : M-TRAN modules (AIST) b) : SWARM-BOT (EPFL) c) : Polybot (PARC)

easily used in unstructured environments like after an earthquake (Casper and Murphy (2003)). Variable geometry robots which are able to adapt their shape to the ground allow a best clearing capability for example by reducing the dimensions to pass into narrow openings (Paillat et al. (2008b)). For general purpose missions we believe that the best compromise between design complexity, reliability, cost and clearing capabilities is the Variable geometry single tracked robots category (Kyun et al. (2005)).

3. B2P2 PROTOTYPE

The main interest of VGSTV (equipped with deformable tracks or not) is that it is practicable to overcome unexpected obstacles (Kyun et al. (2005)). Indeed, thanks to the ability to change their shape, the clearance of a rock in rough terrain will be more smoothly with a VGSTV (e. g. Fig 3 and 4) than with a VGTV (Fig. 2). This kind of robot was studied by Iwamoto and Yamamoto (1983) in the early eighty's. It was about a single tracked vehicle equipped with an actuated articulation to move up and down its front part (Fig. 6). Obviously the tension of the tracks had to be maintained during the movement ; this was managed by a mechanical system equipped with a spring to give some smoothness to the tracks. A commercial VGSTV called Micro VGTV (Fig. 2a) is equipped with this kind of technology. Our work is inspired by these researches, unlike existing robots, the tension of the tracks is actively controlled on our protoype. It allow us to choose the tension of the tracks in regard to the ground configuration as illustrated on Fig. 7(c) and (d).

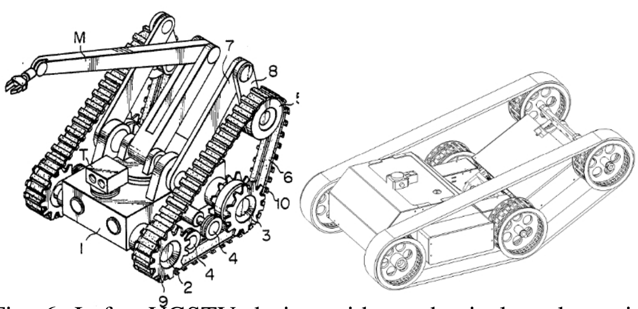

Fig. 6. Left : VGSTV design with mechanical track tension system developed by Iwamoto and Yamamoto. Right : B2P2 prototype (active system)

Indeed, the solution designed allows our robot to adopt classical postures of VGSTV (Fig. 7(a), 7(b) and 7(c)), but also other

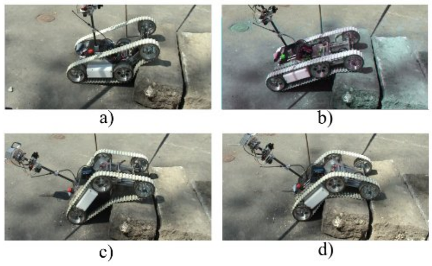

Fig. 7. B2P2 : clearing of a curb

interesting positions. On Fig. 7 B2P2 is clearing a curb of 30 cm height. The position of the robot on Fig 7(c) can also be obtained with the Micro VGTV, but it is a non-safety position and B2P2 is close to topple over. On Fig. 7(d) the tracks have just been released. They take the shape of the curb and it can be cleared safely. This last configuration outlines the interest of using an active system instead of a passive one. Further information about the mechanical conception of B2P2 can be found in Paillat et al. (2008b).

4. AUTONOMOUS STAIRCASE CLEARING

In autonomous stair climbing with UGVs, many information have to be computed from several sensors. As example, Xiong and Matthies (2000) proposed a vision based algorithm which perform an edge detection allowed for estimation of the heading angle θ and the centre position $\frac{d_L}{d_R}$ (see Fig. 8) and regulate the tracks speed during the clearance. However the top speed of the vehicle was limited due to the time between measurements. Lu and Manduchi (2005) proposed a curb detection algorithm based on stereo-vision which could really help to compute autonomous stair climbing. Nevertheless, the detection rate ($4Hz$) constrained the robot top speed. Helmick et al. (2002) gave a set of new estimation and control algorithms to improve the speed, accuracy and effectiveness of autonomous stair climbing based on a multi sensor approach (3 gyroscopes, a 2 DoF electrolytic tilt sensor, a pair of cameras, and a LADAR).

This kind of control only guaranty a straight climbing of the

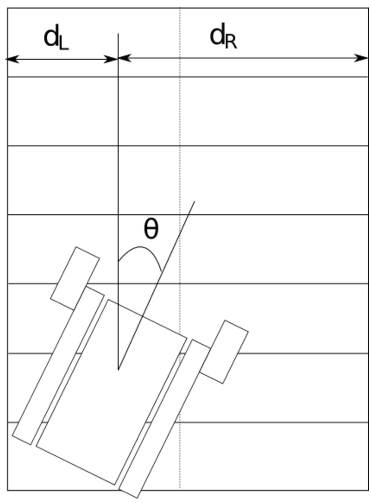

Fig. 8. Top View of a curb clearance

stairs (to avoid steering problems). As shown by Mourikis et al. (2007) it gives a high reliability with PackBot-like robot ; e. g. robots equipped with flippers of negligible weight which of course cannot move their centre of gravity.

In the next sections, we present preliminary results of autonomous staircase clearance. Unlike previous works, the proposed controller is based on learning techniques. Our goal is to design a reactive controller that can be adapted to the environment. Previous works on machine learning applied to robotics Nolfi and Floreano (2000) have proved that this kind of controller can provide efficient behaviour with few sensor information. We effectively believe that staircase clearance can be performed without image processing that is generally expensive in term of computation. Moreover, previous work mainly focused on the heading angle controler, but generally do not consider the motion of the centre of mass during climbing. Obviously, by moving the front part of our prototype, we control the centre of gravity in our robot. However, the controler presented below could work concurrently with heading angle controler developed in previous cited work and offer more adaptability when using VGSTV.

5. BALANCE

In order to perform an autonomous stair climbing, it seems important to define the criterion which is able to guaranty the balance of the robot in the staircase while moving up and down the front part. This section quickly presents a survey performed on our prototype to identify the balance criterion which is needed in case of staircase clearing followed by the choices made to compute a command to climb staircases.

5.1 Balance criterion with B2P2

The balance criterion studied here was the ZMP (Zero Moment Point), widely used for the stability of humanoid robots and the Centre of Gravity (CoG). Previous theoretical works and experiments have proved the ZMP efficiency (Vukobratovic and Borovac (2004)). It consists in keeping the point on the ground at which the moment generated by the reaction forces has no component around x and y axis (Kim et al. (2002) and Kajita et al. (2003)) in the support polygon of the robot. When the ZMP is at the border of the support polygon the robot is teetering. Unlike the ground projection of the centre of gravity, it takes into account the robot's inertia. Detailed information about the computation of this criterion can be found in Paillat et al. (2008a).

The following presents the numerical computation of those criterion in the case of a tele-operated clearance of a staircase (staircase set of 15 cm risers and 28 cm runs) with an average speed of 0.13 $m.s^{-1}$ (Fig. 10). The robot is equipped with a 2-axis inclination sensor that provides rolling and pitching. Data have been stored during the experiments and the models (CoG and ZMP) have been computed off-line. This computation does not take into account the tracks' weight which is negligible in regard to the robot's weight.

The goal of this experiment was to determinate the difference between ZMP and CoG during a clearance. Fig. 9 presents the evolution of the ZMP (left) and the difference between those two criterion (right) during all the clearance. P_1, P_2 and P_3 represent the projection on the ground of three points of the robot. P_1 corresponds to the second axle of the robot (the rotation axis of the front part). P_2 corresponds to the third axle position when the angle between chassis and front part is zero, and P_3, the real position of the third axle.

The clearing of a staircase can be divided into three parts (noticed $A1$, $A2$ and $A3$ on the Fig. 9) which corresponds to the clearing of the first stair, the clearing of the middle stairs and the clearing of the final stair.

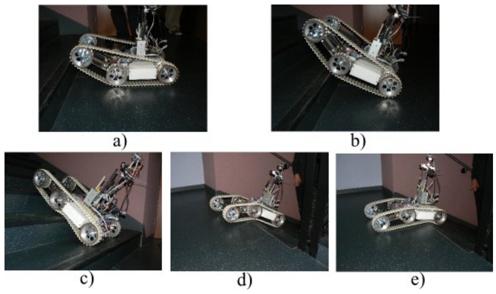

Fig. 10. Clearance of a staircase

The clearance of the first step First of all, the robot is approaching while moving up the front part (Fig. 10(a)) in order to go onto the first step. Then, it has to move forward and move down the elevation articulation in order to keep the stability (Fig. 10(b)). Once the robot is step onto the first stair, the operator have to switch in the next configuration. The area noted $A1$ on Fig. 9 shows the evolution of the ZMP projection during the clearance of the first step. Note that the tracks are tense when the front part is rising up.

The clearance of the middle steps This stage starts in the position noticed on Fig. 10(c). By moving forward, the robot naturally climbs the stairs. At each step, the robot is gently swaying when the ZMP is passing over the step. This phenomenon is illustrated by the oscillation of the ZMP which are visible on the area noted A2 on Fig. 9. Note that, this oscillation is dependant on the ratio between the size of the robot and the size of the steps ("size-step" ratio). It fully disappears when the length of the robot is superior to the size of three steps. On the other hand, oscillations may be more important until reaching a "size-step" ratio where the robot cannot climb the step.

The clearance of the final step The robot is moving forward while moving down its front part (Fig. 10(d)). This operation brings the ZMP closer to the limits of the support polygon, i.e. the corner of the last step. This operation allows a smooth swing of the ZMP. Area A3 on Fig. 9 shows the evolution of the ZMP during the clearing of the last step.

As it is shown on Fig. 9, the average difference between the ZMP and the COG is insignificant (about 0.21%). Moreover, the two peaks (A and B) on the Fig. 9 are not due to the dynamics of the system but to measurement errors. As the acceleration is measured with the encoders (linked to the motor shaft), when the tracks slip, the measurement is erroneous. The ZMP is computationally more expensive, needs more sensor measurements and the difference with the CoG is negligible. For these reasons, we conclude that the CoG seems well suited for this kind of experiments and will be considered in the following. Anyway, in the case where fast obstacle clearance may be necessary, the CoG may not longer be considered and the ZMP must be used instead.

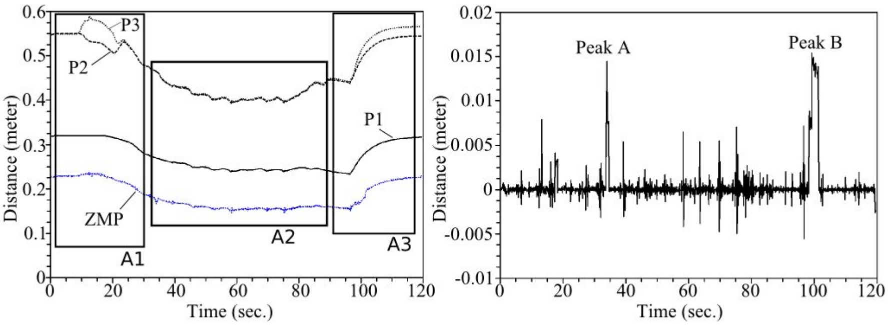

Fig. 9. Experiment's results. The left chart represents the evolution of the ZMP and the right one, the difference between CoG and ZMP.

6. AUTONOMOUS STAIR CLIMBING

The purpose of the following is to present a reactive autonomous staircase climbing controller. This study was performed through a home made C++ software which simulates the behavior of a VGTV in staircase climbing situations. The simulator is based on the model of our prototype B2P2. As explained previously, the CoG is considered as balance criterion in the simulations. The system presented here consists in controlling the elevation of the front part (e.g. the shape of the robot and implicitly the position of CoG).Currently, the tension of the tracks is controlled by a man-programmed algorithm that automatically adapts the shape of the robot according to ground.

6.1 Entries of the system

The system has to be able to react differently in regards to the climbing stage. So, entries have to differ according to the stage (first step, middle steps, final step). The chassis inclination measurement allows to check out the first stage (if the ground is plane) but does not help to conclude about the two others stages (Fig. 11). On the other hand, a distance sensor could check out the last stage as it is shown on Fig. 11. So considering that the robot is always parallel to the step in front of it, the inclination and distance sensors could be sufficient to achieve an autonomous staircase climbing.

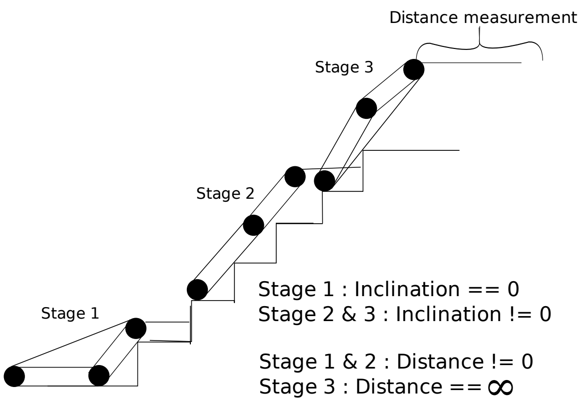

Fig. 11. Stage decomposition during climbing

6.2 Sensors

Several IR distance sensors are mounted on a mobile system coupled with the inclination sensor in order to always measure the distance between the robot and the step in front of it (Fig. 12). Side Sensors are used to keep the vehicle parallel to the steps. Front sensors allow direct measurement of the distance. Sensors' measurements can be merged to increase the accuracy. Besides, interval analysis algorithms could be used as in Sliwka and Jaulin (2008) to prevent a breakdown and to increase the system reliability.

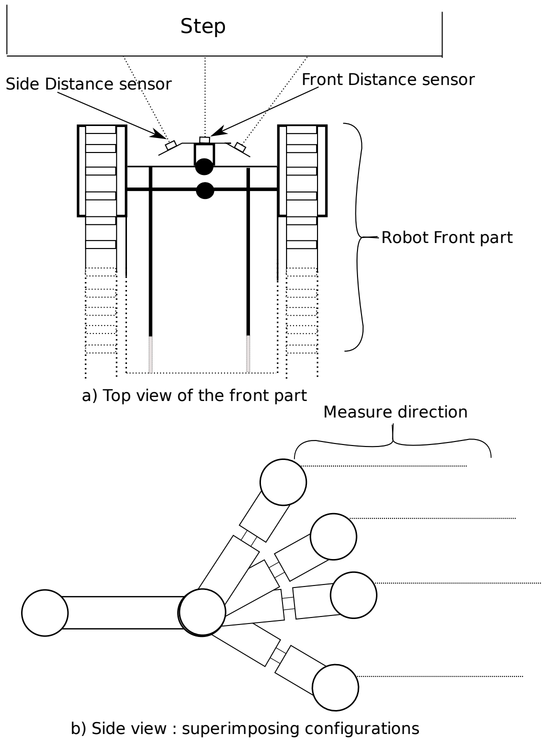

Fig. 12. Distance measurement system

6.3 Controller

As explained by Nolfi and Floreano (2000) genetic algorithms can be used to train and optimise control systems. Typically, Artificial Neural Networks (ANNs) are often used as control systems for obstacle avoidance or grasping tasks (Lucidarme (2008)) because such controller can approximate a wide range of mathematical functions. An ANN is composed of several units linked by weighted connections w_{ij}. Each unit *i* has entries x_j and one output y_i which is a function $\sigma()$ of $\sum_j^N(w_{ij}.x_j)$ where w_{ij} corresponds to the weight of the link between two neurones. Theoretically, neurones are organised in layers to perform a neural network. This network can be feed-forward (signal travel from inputs units forward to output units) or recurrent (there may be feedback connections from neuron in upper layer or in the same layer). As introduced, in the case of autonomous staircase climbing with a VGSTV as B2P2, the system have to control the elevation of the front part according to the position of the robot in the staircase. Otherwise, the output of the network is the elevation of the front part. Consequently the neural network architecture chosen is a feed-forward network with one hidden layer (Fig. 13) that must be addressed to approximate non linear functions. Indeed, a recurrent network does not seem useful, because a variation of the output (elevation angle) includes a variation of the network entries (IR distance sensors and inclination sensor).

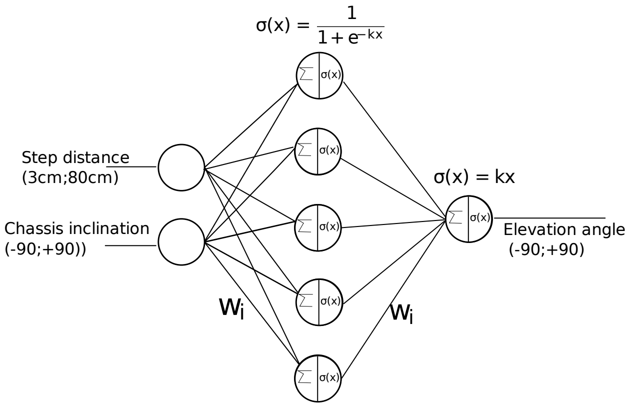

Fig. 13. Neural Network Model

6.4 *Evolutionnary training*

Chromosome In the controller, all the parameters are known except the 15 synaptic weights (w_i) which are deduced by an evolutionary algorithm based on a classical genetic approach. As the structure of the network has been fixed, only those weights have to be optimised. Consequently, a chromosome is only composed of the weights W_i.

w_1	w_2	...	w_i	...	w_{14}	w_{15}

Table 1. Chromosome description

Selective reproduction Each generation is composed of 200 sets of chromosomes composed of fifteen parameters randomly selected into $[-1,1]$. After each generation, a selective reproduction is performed in order to compute the next generation. Here this selection is roulette wheel based that allow the best individual to be statistically selected more frequently. Otherwise :

$$p_i = \frac{f_i}{\sum_i^N f_i}$$

Where :

- p_i : probability of selection for the individual i,
- f_i : fitness of the individual i,
- N : number of individual in the previous generation.

A selection process is performed for each chromosome element (e. g. fifteen times) to compute the next generation. However, the best individual of each generation is duplicated for the next generation without selective reproduction.

Mutation In order to prevent local minimums in the results, a mutation step is necessary. Indeed, if an individual obtain much higher fitness than the rest of the population, it could soon dominate the population and cause premature convergence. The mutation process consists in replacing by a random value in the range $[-1,1]$ a randomly selected gene (chromosome element) for 10% of the new generation.

Fitness Function As the goal is to climb staircases, the fitness function must be linked to the number of steps cleared. As this parameter is discrete, we combined it with another parameter that minimises the energy (directly linked to the elevation part movement). Moreover, minimising the energy provides smooth trajectory of the robot. It is expressed as follow :

$$f_i = \frac{N_{steps}}{E}$$

Where :

- f_i : fitness of the individual i,
- N_{steps} : Number of steps cleared by individual i,
- E : parameter depending on the average speed of the front part (V)

$$E = \begin{cases} 1 & \text{if } V < \text{threshold} \\ V & \text{otherwise} \end{cases}$$

6.5 *results*

The simulation was performed with a classical staircase sets of five steps of 15 cm risers and 25 cm runs. Fifty generations was tested in order to have a characteristic convergence (Fig. 14). Simulation results are shown on Fig. 15

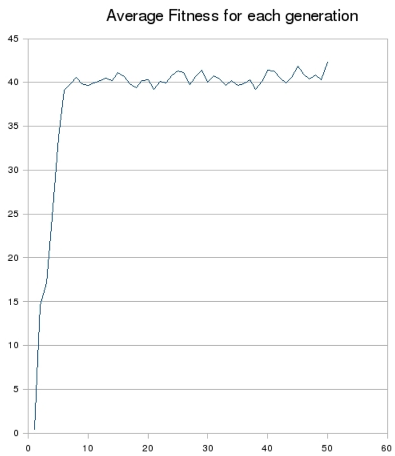

Fig. 14. Generation convergence

In order to evaluate how generic are the produced results, the best individual has to get over several kind of staircases as described in table 2. The percentage of cleared steps is indicated according to the length and the height of the steps. Note that the 25 cm is the maximum step height that the prototype is able to clear in tele-operated staircase clearance.

The controler seems to be able to perform an autonomous staircase clearing in regard to the poor information given by the environment.

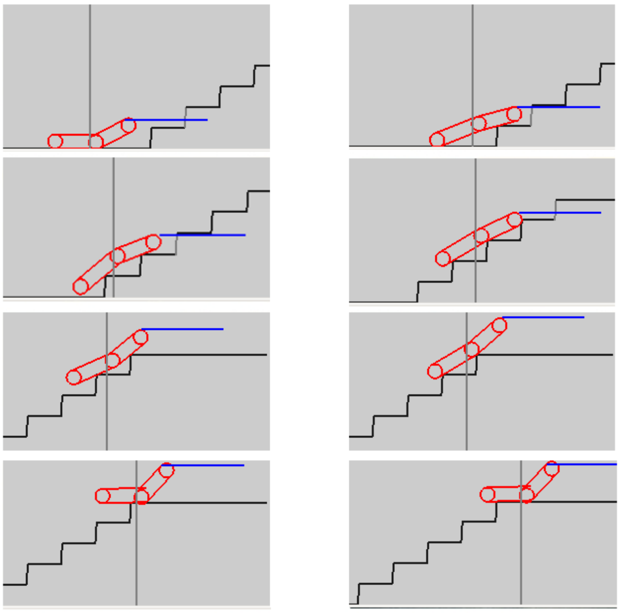

Fig. 15. Staircase climbing simulation results

Step length (cm) \ Step height (cm)	15	20	25	30
15	100%	100%	100%	100%
20	60%	80%	100%	100%

Table 2. Results

CONCLUSION

This paper presents a way to climb staircases with classical VGTVs by using their ability to modify their geometry in order to adapt themselves to the ground. It consists in a neural network which compute the elevation of the robot's front part in respect to its inclination and the distance between it and the next step. This controler could be used concurrently to classical UGVs staircase climbing algorithms which guaranty the steering during climbing and improve its efficiency.

We are currently working on the implementation of this results on our prototype B2P2. If experimental results are conclusive, more optimisations could be thought in order to increase the reliability and the adaptability of the system.

REFERENCES

Ben-Tzvi, P. and Goldenberg, A.A. (2007). A novel control architecture and design of hybrid locomotion and manipulation tracked mobile robot. Internationnal Conference on Mechatronics and Automation.

Carlson, J. and Murphy, R.R. (2005). How ugvs physically fail in the field. *IEEE Transactions on robotics*, 21(3), 423–437.

Casper, J. and Murphy, R.R. (2003). Human-robot interactions during the robot-assisted urban search and rescue response at the world trade center. *IEEE Transactions on systems, man, and cybernetics*, 33(3), 367–384.

Clement, G. and Villedieu, E. (1987). Variable geometry track vehicle. Us patent.

Guarnieri, M., Debenest, P., Inoh, T., Fukushima, E., and Hirose, S. (2004). Development of helios vii : an arm-equipped tracked vehicle for search and rescue operations. *IEEE/RSJ Int. Conference on Intelligent Robots*.

Helmick, D.M., Roumeliotis, S.I., McHenry, M.C., and Matthies, L. (2002). Multi-sensor, high speed autonomous stair climbing. Internationnal Conference on Intelligent Robots and Systems.

Iwamoto, T. and Yamamoto, H. (1983). Variable configuration track laying vehicle (us patent).

Kajita, S., Kanehiro, F., Kaneko, K., Fujiwara, K., Harada, K., Yokoi, K., and Hirukawa, H. (2003). Biped walking pattern generation by using preview control of zero moment point. Proceedings of the 2002 IEEE Internationnal Conference on Robotics ans Automation.

Kim, J., Chung, W.K., Youm, Y., and Lee, B.H. (2002). Real time zmp compensation method using null motion for mobile manipulators. Proceedings of the 2002 IEEE Internationnal Conference on Robotics ans Automation.

Kyun, L.S., Il, P.D., Keun, K.Y., Byung-Soo, K., and Sang-Won, J. (2005). Variable geometry single-tracked mechanism for a rescue robot. *IEEE International Workshop on Safety, Security and Rescue Robotics*, 111–115.

Lu, X. and Manduchi, R. (2005). Detection and localization of curbs and stairways using stereo vision. Internationnal Conference on Robotics and Automation.

Lucidarme, P. (2008). Evolution of a mobile robot's neurocontroller on the grasping task. Internationnal Conference on Informatics in Control, Automation and Robotics.

Misawa, R. (1997). Stair-climbing crawler transporter. Us patent.

Mourikis, A.I., Trawny, N., Roumeliotis, S.I., Helmick, D.M., and Matthies, L. (2007). Autonomous stair climbing for tracked vehicles. *The Internationnal Journal of Robotics Research*, 737–757.

Nolfi, S. and Floreano, D. (2000). *Evolutionnary Robotics*. The MIT Press.

Paillat, J.L., Lucidarme, P., and Hardouin, L. (2008a). Study of dynamics and zmp computation for a vgstv prototype. Internal report available at http://www.istia.univ-angers.fr/lisa/b2p2/b2p2.html.

Paillat, J.L., Lucidarme, P., and Hardouin, L. (2008b). Variable geometry tracked vehicle, description, model and behavior. Conference Mecatronics.

Paillat, J.L., Lucidarme, P., and Hardouin, L. (2008c). Variable geometry tracked vehicle (vgtv) prototype, conception, capability and problems. Conference on Humans Operating Unmanned Systems.

Sliwka, J. and Jaulin, L. (2008). Robust localization for an easier tele-operation. Conference on Humans Operating Unmanned Systems.

Vincent, I. and Trentini, M. (2007). Shape-shifting tracked robotic vehicle for complex terrain navigation: Characteristics and architecture. Technical memorandum, Defence R and D Canada.

Vukobratovic, M. and Borovac, B. (2004). Zero-momment point - thirty five years of its life. *Internationnal journal of humanoid Robotics*, 1(1), 157–173.

Xiong, Y. and Matthies, L. (2000). Vision-guided autonomous stair climbing. Internationnal Conference on Robotics and Automation.