Design of a Cockroach-Like Running Robot for the 2004 SAE Walking Machine Challenge

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Abstract

Captain Basile is a robot inspired from the cockroach and built to participate at the SAE *Walking Machine Challenge* 2004, an undergraduate competition of walking robots.

The robot weighs 35 kg and is 86 cm long, 58 cm wide and 38 cm tall. Initially validated by the use of dynamic simulations, this pneumatic actuated hexapod is characterised by specialized legs, passive visco-elastic elements and a self-stabilizing posture. This mechanical system allows straight line running at 1.11 m/s and turning at 33.2 degrees per seconds with a simple feedforward control system.

This paper presents *Captain Basile*, its design, performances and the results from speed experiment.

Keywords: Cockroach robot, Hexapod, Specialized legs.

1 Introduction

Locomotion over uneven ground has always been a difficult challenge. Many wheel designs exist but have limited performances on uneven ground at high speed. Observations on cockroaches [3, 4, 5 and 6] suggest that legged robots could achieve better performances in this field than they did in the past.

This is why, three years ago, a group of students from the *Université de Sherbrooke* (Canada) was created to take up the challenge of designing and building an insect-like running robot that would perform at the *Society of*

Automotive Engineers (SAE) *2004 Walking Machine Challenge* (WMC 2004). This paper gives an overview of the robot named *Captain Basile*, followed by an analysis of its performances.

2 Problem statement

The *SAE Walking Machine Challenge* is a competition where the speed, the force to weight ratio, the autonomy and the all-terrain performances of walking machines designed by undergraduate students are evaluated.

To complete the competition events, the robot must be able to climb over 20 cm obstacles, to grasp and carry a 10x10x10 cm dense wood block and to carry a charge of 10 kg or more over 18 meters. The rules also limit the overall size to a 1x1x1 meter box.

The fastest robots at the WMC 2002 had a maximum speed of 0.2 m/s on flat ground and 0.02 m/s at the obstacle challenge [1]. As speed is a criterion in all the events of the competition, there is a big opportunity to improve these performances.

3 Design inspiration

Many recent studies on cockroaches [3, 4, 5 and 6] propose a new approach to build walking robots that use insects as a source of inspiration to improve the speed and all-terrain performances. Robots like *Sprawlita* [6], *Whegs I & II* [10] and *RHex* [12] show that rather than just copying the morphology of a cockroach, the solution is to better understand the way it dynamically walks and to implement the fundamental characteristics that explain its performances in a functional and simple robot.

These studies suggest that insect inspired robots should exhibit:

- **Self-stabilizing posture:** A self-stabilizing posture, provided by a low center of mass and a large triangle of support where kinetic energy and leg thrust is used to stabilize the walking pattern [3].
- **Specialized legged function:** Hind legs propel the robot forward, front leg are used to go over obstacles while middle do something in-between [7, 5]. The positioning of the rear foot during climbing prevents the cockroach from falling on its back [9].
- **Compliance:** A well chosen visco-elastic structure provides compliance which is useful to maintain a good contact with the ground [6] and to absorb the foot impact without any active control.

- **Timed, open-loop/feedforward control:** These three characteristics, when embedded in a properly tuned mechanical system, simplify the control system so that only feedforward control is necessary in order to obtain a stable and fast gait.

As a walking machine with less actuators tends to have a better power to mass ratio [10], effort should be made to reduce their number to the strict minimum. This is also useful as this robot has to be power autonomous.

4 Simulations

In order to validate how each of these observations can be applied to reach the targeted goals, *MSC.visualNastran 4D*, a physics-based simulation package and Matlab/Simulink was used.

A simple model was initially used to test the general concept of insect-like locomotion. Then, a second model (**Fig.1.**) was used to select and position the proper components and to tune the feedforward parameters.

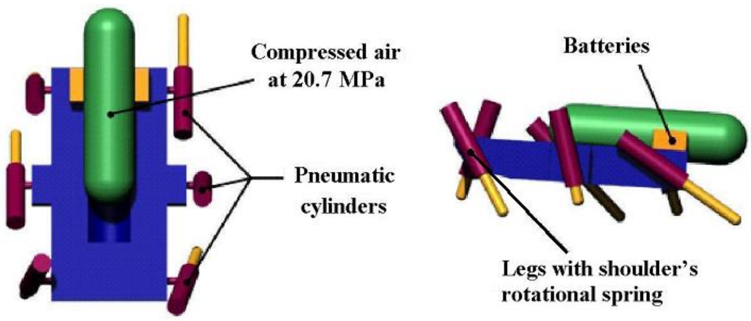

Fig. 1. Model used in the component-sizing simulations

These simulations confirmed that the robot can behave as insects and gave a few more insight on the construction:

- Open-loop control is adequate for straight line running with minimal drifting of about 1% [3].
- Compliance, given by the shoulder spring, is enough to passively produce the proper motion needed by running.
- The position of the center of mass should be between middle and hind legs to allow proper use of those legs for propulsion [3].
- Leg thrusting force should be approximately three times the weight of the robot divided by the supporting legs [8].

- The optimal angles needed by the legs to work are similar to those of the cockroaches [7].
- The feedforward pattern used for running doesn't require any modifications to allow climbing of 20 cm high obstacles.
- Alternating tripod gait is better suited for straight line running than pairs of legs in phase, being more stable. The second method turned to be better for climbing than tripod gait [11].

5 Mechanical system

The robot (**Fig.2.**) weighs 35 kg and is 86 cm long, 58 cm wide and 38 cm tall. Compressed air was chosen as a power source due to its good energy density and its high discharge rate [9]. The 1.9 cm diameter double-acting air cylinders are ideal as their linear action is compliant and directly used to create leg thrusting. Two 2.7 litres air tanks at 20.7 MPa provide, through a regulator, the 827 kPa needed for the six cylinders.

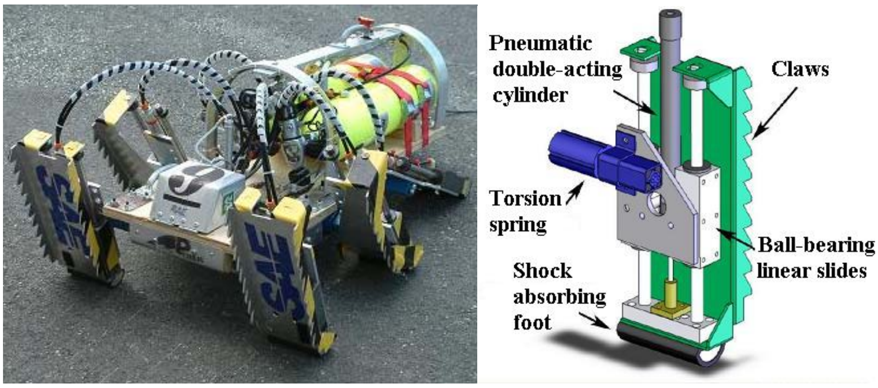

Fig. 2. Actual state of *Captain Basile* and rear view of the front leg subsystem

The robot has 12 degrees of freedom (DOF), two per leg. The six pneumatic cylinders controlled with on-off commands represent the active DOF of the robot. Each leg is linked to the body by a passive rotational spring (**Fig.2.**). The ball-bearing linear slides protect the cylinders from radial stresses caused by the impacts of locomotion. The rubber-coated feet were designed to absorb impacts and to maximise the friction with the ground while the claws were used to increase the climbing performances.

The frame of the robot is made of wood as this affordable and easy to use material is strong and light. This frame allows fast modifications and is well suited for a prototype. The robot also uses a sticky trap actuated by a seventh air cylinder to grasp objects on the floor.

6 Control system

The control system (**Fig.3.**) is divided into two parts: electronics onboard the robot and the human control interface. Onboard electronics is constituted of two nodes communicating via a CAN (Controller Area Network) protocol; the Power Management Unit (PMU) and the Motion Controller.

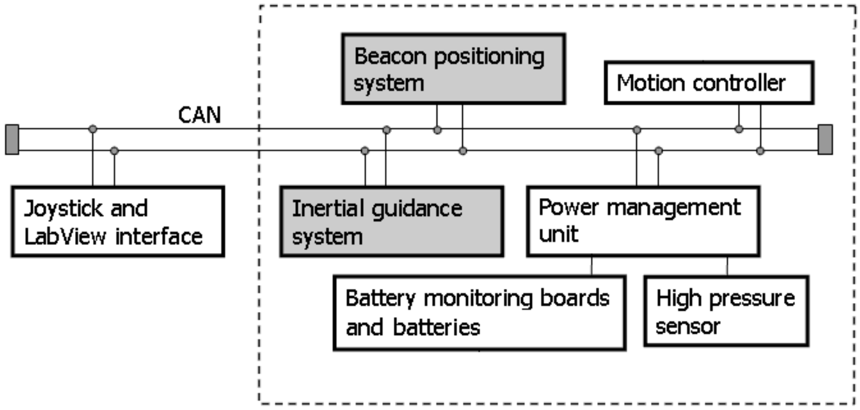

Fig. 3. Control system of the robot. Components in the dashed box are onboard electronics. Components shaded aren't installed on the robot yet. The central bus is the Controller Area Network.

The PMU acts as a charger, a power supply and a monitor of the battery level and as well of the tanks pressure. This fully configurable unit, presented in [2], allows the NiMH batteries to be recharged without removing them from the robot while supplying the other electronics and the valves with an external source. It uses small battery boards to calculate the number of charges used, measure battery temperature and store data.

The PIC18F458 based Motion controller receives high level commands to generate the cyclic commands for the legs. These valve commands are generated at 3 Hz with a resolution of 2 ms. It allows autonomous actions to be executed as well as feedback from the optional end-stroke sensors.

The human control interface is implemented in *National Instrument's LabVIEW* to allow an operator to use a game pad or the console to send commands and analyse feedback from the sensors. Both onboard electronic units can be autonomous or controlled through the control interface.

7 Performances

After a few simple tuning through simulations and experimental optimisation, *Captain Basile* reaches a top speed of 1.11 m/s (1.25 body length per second). In straight line running, its two air tanks provide about 2.5 minutes of autonomy. Despite its speed, an operator can easily position the robot with a precision of 1 cm. A turning speed of 33.2 degrees per second is achieved by pushing only with the legs on one side.

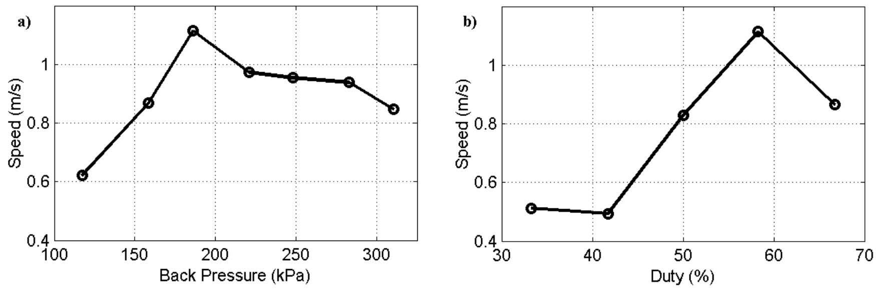

Fig. 4. a) Speed as a function of the back pressure, with an active pressure of 745 kPa. The leg thrusting period is 0.3 s and the duty cycle is 50 %.
b) Speed as a function of the duty cycle, with an active pressure of 745 kPa. The leg thrusting period is 0.3 s and the back pressure is 186 kPa.

Fig.4. a) shows the influence of the pressure that retracts the cylinders on the speed of the robot. To simplify the pneumatic system, the back pressure is always active. The difference between the back and the thrusting pressure should be maximized. However, a too low back pressure can't retract the legs efficiently, slowing the robot. This experiment showed that the optimum pressure for the greatest speed is around 180 kPa, but 220 kPa is more appropriate for better stability with less vertical oscillation of the center of mass.

Fig.4. b) shows the influence of the duty cycle on the speed of the robot. The leg duty cycle represents the percentage of time where each cylinder is commanded to be in extension. A too short duty cycle doesn't give the legs the time to push efficiently. With a too long duty cycle, the legs stay on the ground even after their useful pushing action and slow the robot. The best experimental duty cycle is around 58%.

The robot is also able to grasp a 10x10 cm block or to carry a 10 kg payload, 28% of its own weight, without significant speed loss. Climbing performances aren't as good as simulated; the actual robot is able to climb obstacles 10 cm high while 20 cm obstacles were climbed in simulation.

8 Future work

In addition to various ameliorations, further experiments based on the way insects turn [5] are being done. Climbing and the influence of the claws are analyzed in order to better understand the difference between simulations and experimental results and to improve the all-terrain performances. For now, beacon positioning and inertial guidance are under investigation.

9 Conclusion

There is a new generation of walking robots emerging that, unlike their slow, complex and heavy predecessors, rely on abstracted biological principles to be faster and more agile. There is a feeling that this relatively recent approach could lead to robots with better performances. The current work relies on studies of an insect, the cockroach, to design an agile and strong but yet a simple walking machine.

Initially validated by the use of dynamic simulations, this robot includes specialized-legged functions, passive visco-elastic elements and a self-stabilizing posture. This mechanical system allows straight line running with a simple open-loop feedforward control system. It was the fastest robot at the WMC, and work is underway to further optimize the prototype.

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References

1. http://www.Mines.edu/fs_home/jsteele/wmc, [2002] CSM 2002 SAE Walking Machine Challenge.
2. Éric Lespérance, Alexis Lussier Desbiens, Marc-André Roux, Marc-André Lavoie and Philippe Fauteux, *Design of a Small and Low-Cost Power Management Unit for a Cockroach-Like Running Robot*, IROS 2005.

3. L. Ting, R. Blickhan, and R. Full, “Dynamic and static stability in hexapedal runners,” *Journal of Experimental Biology*, no. 197, pp. 251-269, 1994.
4. T. M. Kubow and R. J. Full, “The role of the mechanical system in control: a hypothesis of self-stabilization in hexapedal runners,” *Royal Society of London*, no. 354, pp. 849-861, 1999.
5. D. L. Jindrich and R. J. Full, “Many-legged maneuverability: dynamics of turning in hexapods,” Journal of experimental biology, no. 202, pp. 1603-1623, 1999.
6. J. E. Clark, J. G. Cham, S. A. Bailey, E. M. Froehlich, P. K. Nahata, R. J. Full, and M. R. Cutkosky, “Biomimetic design and fabrication of a hexapedal running robot,” *IEEE International Conference on Robotics and Automation*, May 2001.
7. R. Kram, B. Wong, and R. J. Full, “Three dimensional kinematics and limb kinetic energy of running cockroaches,” *Journal of Experimental Biology*, no. 200, pp. 1919-1929, 1997.
8. M. H. Raibert, *Legged Robots that Balance*, M. Press, Ed., Cambridge, MA, 1986.
9. M. B. Binnard, “*Design of a small pneumatic walking robot*”, Master of Science, Massachusetts Institute of Technology, Jan. 1995.
10. Thomas J. Allen, Roger D. Quinn, Richard J. Bachmann, Roy E. Ritzmann, “*Abstracted Biological Principles Applied with Reduced Actuation Improve Mobility of Legged Vehicles*”, Case Western Reserve University
11. James T. Watson, Roy E. Ritzmann, Sasha N. Zill, Alan J. Pollack, “*Control of obstacle climbing in the cockroach, Blaberus discoidalis*”. Case Western Reserve University, 2001.
12. U. Saranli, M. Buehler, D.E. Koditschek. *"RHex: A Simple and Highly Mobile Hexapod Robot."* The International Journal of Robotics Research 20 (2001) July 616-631.