CONCEPTUAL DESIGN OF A SOLID-PROPELLANT SELF-POWERED ROBOT

Fernando de Paula Leite Castor
Paulo Sérgio dos Santos Bastos
Jorge Audrin Morgado de Gois [1]
Departamento de Engenharia Mecânica e de Materiais
Instituto Militar de Engenharia
Praça General Tibúrcio 80, Praia Vermelha
Rio de Janeiro - RJ - CEP 22290-270
[1] audrin@ime.eb.br

Abstract. *This paper shows the main ideas behind the development of the concept of a solid-propellant self-powered robot and draws the outlines for the design of a prototype. The proposed approach utilizes a double-base solid propellant to generate hot gas, which is employed to power a pneumatic-type actuation system. This propellant is usually used in rockets because of its high energy/weight relation, what makes it very appropriated for extremely power-consuming applications. The actuation system is designed and modelled respecting the restrictions due to the use of hot gas. Its very unique dynamical behaviour as well as a suitable control system are discussed. The solid-propellant design approach is then compared to a traditional design, using battery-powered dc motors, to a system consisting of a combustion-engine-powered hydraulic actuation and finally, to a system based on liquid propellant. Projections based on the single-degree-of-freedom robot model indicate that the same system, when employed at a robot with many degrees-of-freedom can offer a much higher energetic performance.*

Keywords: *solid-propellant, self-powered robot, pneumatic actuation.*

1. INTRODUCTION

Nowadays, robots are largely employed in different areas and activities, but their use is slowed down by a few technological restrictions and, when considering mobile robots, power supply is usually the most serious. Actually, the energetic deficiency in current mobile robots means a poor relation between available power and the system mass in the robot, and not a small amount of available energy.

Wheeled robots have a relative good power/mass relation, but they depend on a suitable ground to operate properly, what is not always present (Dunningan, 1996). In such environments, legged robots would represent a good solution, but they suffer from a very poor power/mass relation, what very often makes impossible to employ them in such tasks, which still have to be executed by humans. Most of legged robots walk in a quasi-static equilibrium, requiring low actuation forces and torques, reducing their energy consumption; on the other hand, these robots have their dynamical performance strongly constrained.

The locomotion task is, in general, the most power consuming task of legged robots, which may be considered as executed by two main systems: power source and actuation system. The first concerns the set of things responsible for energy storage (batteries, fuel and its tank, accumulators, etc…), while the latter represents the devices responsible for transforming the energy into controlled mechanical work (motors, pumps, hydraulic cylinders, etc…).

The aim of this work is to propose a locomotion system (i.e., power source and actuation system) which enables a faster dynamical behavior for the robot through the improvement of its power/mass relation. In this way, a new locomotion system, based on the use of solid propellant, is proposed, because this kind of propellant presents a high specific power (Army Science Conference, 2000), providing an enormous amount of energy from a small mass of propellant in a very short time.

In the proposed system, the energy is delivered by a gas generator in the form of hot gas – result of the propellant combustion – and can be used in a pneumatic system. In order to use efficiently the high amount of available power in such a system, the robot has to present a completely new dynamical behavior, what is briefly analyzed in this work. Later in the text, different implementations for gas generation system are analyzed: an expansion valve, a turbocharger and a variable volume combustion chamber.

2. ROBOT DESIGN

The Actuation Potential A_p (Barth, E.J. et al. 2003) is a suitable figure of merit to quantify the energetic performance of power supply and actuation system. This performance index is composed by three parameters of primary interest to provide an optimal energetic performance: the energy density e_s, the maximum power density p_a and the efficiency of converting energy from the power source to controlled mechanical work η. Thus, the index can be written as in Eq. (1):

$$A_p = e_s \cdot \eta \cdot p_a \tag{1}$$

The index expresses a relation between the power available for execution of a specific task and the overall mass of devices responsible for such execution. In this overall mass are included the masses of power supply, actuators, conductors, converters and any other device involved in supplying energy and transforming it into work for the execution of a task. In order to state the necessary parameters for the project of the power supply, it is necessary first to specify the robot kinematics and the actuation system. From the robot structure and the desired movement it is possible to estimate the amount of necessary power and its form, in this case, gas pressure and flow.

2.1. Kinematics

In the search for a system able to develop a highly power demanding dynamics, the specific power seems to be the most important index to consider. That is an encouraging fact towards the use of pneumatic actuators, because they present in general a much higher power density than electric motors (Morgado de Gois, 2007). That can be still improved by the use of a special kind of pneumatic actuators, known as pneumatic muscles, whose advantage relays on their relative low weight due to the small amount of metallic parts, however they work in a single action way, what implies in the use of two actuators to drive a one-degree-of-freedom joint.

The focus of the project is on legged robots, thus the adopted structure is a four legged walking machine. The kinematical characteristics of that structure enable very simple walking patterns for low velocities with static equilibrium (Hiller, M.; Germann, D.; Morgado de Gois, J. A.; 2004), besides many optimal solutions for a fast walk are already available in nature, from the many classes of quadrupeds.

The general structure employed here uses inverted knees (when they bend the feet move forward), present in fast running animals. As a whole new locomotion system is to be proposed, an already existing kinematical structure will be considered as starting point for this work: it was chosen the one present at the quadruped *TomCat* from Allegrobot®, shown in Fig. 1. The mechanical structure of this robot will act as a base for the development of the new propulsion system, thus each electric motor will be replaced by a composition of two pneumatic muscles.

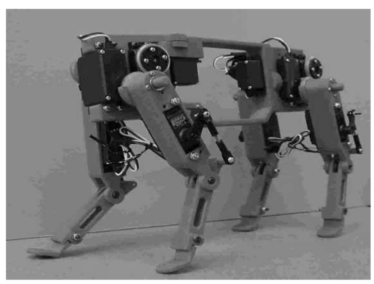

Figure 1 – TomCat Robot

Each leg of the robot has two degrees of freedom, enclosed in two revolute joints (knees and hips), and one more revolute joint is present between the front and rear parts of the body, in order to set the heading of the machine. The contact between each foot and ground has to be modelled according to the walking phase of the specific foot (Morgado de Gois, J. A.; Hiller, M; 2004); the number of degrees of freedom in such constraint may vary from one to four. In Fig. 2 the topology of the robot is sketched with three degrees of freedom (d.o.f.) between each foot and the ground, corresponding to a twist of body and the legs.

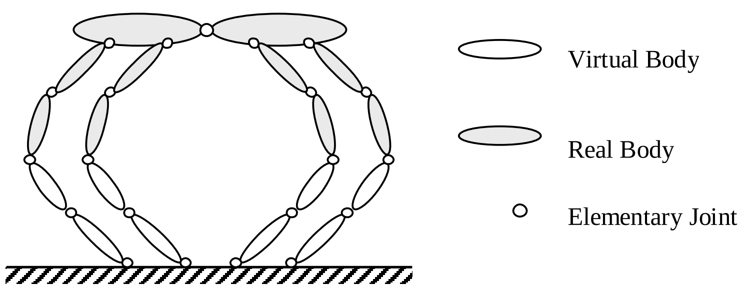

Figure 2 – Kinematical topology

Actually, many different topological structures can be identified as the robot walks:

- straight without slip, for the feet are in contact with the ground there is just one d.o.f. between each foot and ground, for the feet which have no contact with the ground there are three d.o.f. from each foot to the ground.

- in a curved trajectory (the main body parts are not aligned, i.e., the robot turns to the side), for the feet in contact with the ground there are two d.o.f. from each one to the ground, while for the feet without contact, four d.o.f. are present between foot and ground.

The measures used in the work follow the proportions of *TomCat*, however, since it is just 25 cm high, they had to be scaled to fit the legs to the minimal size of actuators.

2.2. Actuation

Due to the topology of the robot, the posterior set of actuators is responsible for the highest forces during the walking process; therefore this set will demand most of the power. The critical operational condition is given by the contraction of all actuators of the posterior set (Morgado De Gois, J.A.; Germann, D.; Hiller, M.; 2003), thus the kinematical design of the leg plays a relevant role when stating parameters of the actuation system.

From the kinematical structure defined in last section it is possible to state the values for the maximal necessary force in the actuators. A set of independent coordinates is defined as $\mathbf{q}$, where each of its components corresponds to the contraction of an actuator. A set of dependent coordinates $\boldsymbol{\beta}$, which completely determines the robot configuration, is constructed so that a set of constraint equations $\mathbf{g}(\boldsymbol{\beta}, \mathbf{q}) = \mathbf{0}$ is derived to describe the kinematical behavior of the robot.

If an explicit solution for $\boldsymbol{\beta}$ as function of $\mathbf{q}$ is found (Greenwood, D.T., 1977), it enables to write $\boldsymbol{\beta} = \mathbf{g}^*(\mathbf{q})$. From this relation is very easy to state the relation between the velocities, as in Eq. 2.

$$\dot{\boldsymbol{\beta}} = \frac{\partial \mathbf{g}^*}{\partial \mathbf{q}} \dot{\mathbf{q}} = J_q(\mathbf{q}) \cdot \dot{\mathbf{q}} \tag{2}$$

In Eq. 2, J_q represents the Jacobean matrix of the set of kinematical constraints with respect to the independent coordinates. If the set $\boldsymbol{\beta}$ is composed of centroidal coordinates, the kinetic energy E of the system may be written as function of the independent velocities in Eq. 3.

$$E(\mathbf{q}, \dot{\mathbf{q}}) = \frac{1}{2} \cdot \dot{\boldsymbol{\beta}}^T \cdot M \cdot \dot{\boldsymbol{\beta}} = \frac{1}{2} \cdot J_q^T \cdot \dot{\mathbf{q}}^T \cdot M \cdot J_q \cdot \dot{\mathbf{q}} \tag{3}$$

Considering all the applied forces, that is, the weights and the actuator forces, a vector of generalized forces $\mathbf{Q}$ may be written, and by use of Eq. 3, Lagrange Equations of motion are written for the system as in Eq. 4.

$$\frac{d}{dt}\left(\frac{\partial E}{\partial \dot{\mathbf{q}}}\right) - \frac{\partial E}{\partial \mathbf{q}} = \mathbf{Q} \tag{4}$$

Now, if the desired velocities for the robot are known, with the help of Eqs. 2 and 4, it is possible to state the inverse dynamics problem and find the values of the force in actuators. In order to have a starting point, some values have to be estimated; thus, the estimated total mass of the robot is 30 kg, height of the hip joints is 60cm and a length of 70cm. As requirement of the project, the robot must be able to jump, starting from rest, as high as its hip; such consideration implies in a moment of 14.7N.m in each joint of the legs. As the revolute joints of the legs will be driven by translational actuators, the movement amplitude and the applied force will be directly connected by the size of the spike (lever which links the actuator and the leg part).

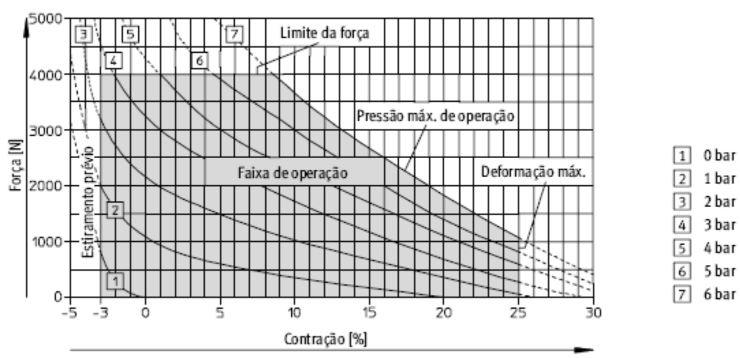

Figure 3 –Force Diagram from pneumatic muscle MAS 40 from Festo®

Taking a length of 4 cm for the spike, we may state the actuator force as 368 N, then using the force diagram shown in Fig. 3 – which corresponds to a pneumatic muscle – it is possible to state the maximal contraction. Stating that the pneumatic system will work at a pressure of 3 bar, from the chart it is seen that a contraction of 24% is needed, what for this size of lever gives a maximal rotation of 130^{o}.

The volume change in such actuators is negligible, what means that the necessary mass flow for an actuation cycle corresponds just to the pressure change. Considering the air as an ideal gas, the volumetric flow is twice the internal volume of the muscle, what will give a volume of 0.502 liter per cycle at 3 bar.

Besides, another restriction is imposed by the use of such actuators: the maximal work temperature. Because of their polymeric constitution, the highest temperature is about 80^{o}C. It means that the gas originated at the propellant combustion cannot be used; therefore an intermediate device for power conversion has to be employed.

3. GAS GENERATOR

The gas generator is a device responsible for burning propellant to produce hot gas, which will work as energy source for the system. Since the propellant is in solid state and already contains the necessary oxygen for the combustion in its constitution, once it starts to burn, it is practically impossible to interrupt the process. Therefore, the propellant should be burnt in small amounts, in order to enable the control of gas generation.

Besides that fact, chemical characteristics of the propellant have to be considered, such as stability and energetic density. One of the most used solid propellant is the family of smokeless powders, but if considered the fact that the energetic density of nitrocellulose is just 1.09MJ/kg (Bittencourt, G.A.; Bandeira, E.L.; 2001), what means that as energy source, nitrocellulose is not as good as gasoline because the former has less energy per unit of mass. On the other hand, the burn rate for nitrocellulose is about 10^{3} times higher than the rate of an ideal air-gasoline mixture, what makes the nitrocellulose able to deliver a much higher power.

Given specially the safety in handling, the selected propellant is the double-base smokeless powder, which presents a flame temperature of 2300^{o}C. This propellant is manufactured in many different forms, including the seven-perforated grain, shown in Fig. 4, which presents small dimensions, what together with the density of 1250 kg/m^{3} comprehends a mass of 0.5 g for the grain. Parallel to that, the geometry of the grain causes a fast gas generation rate.

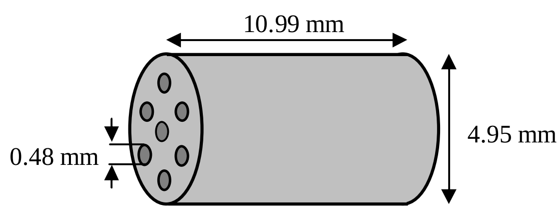

Figure 4 – Propellant Grain

The gas generator will be composed of a combustion chamber, a dispenser and a storage case. The propellant grains are carried in the storage case and inserted in the combustion chamber by the dispenser mechanism. Once in the combustion chamber the propellant is ignited by an electric spark.

3.1. Intermediate System

Because of the high temperatures of the propellant combustion gas, special materials have to be used and the gas cannot be employed directly in any kind of commercial actuators, especially pneumatic muscles. Therefore, an intermediate system has to be developed to provide pressurized gas at low temperatures. Three different systems are proposed and analyzed:

- *Expansion Valve* enables the volumetric expansion of the combustion gas, reducing its enthalpy and consequently its temperature. As the highest operation temperature for commercial actuators is about 100^{o}C, the necessary temperature fall would be 2200^{o}C, what leads to a corresponding pressure fall. That gives an efficiency of less than 20 %, implying in a very low actuation potential; therefore, the use of expansion valve fails in achieving the main goal of this project.

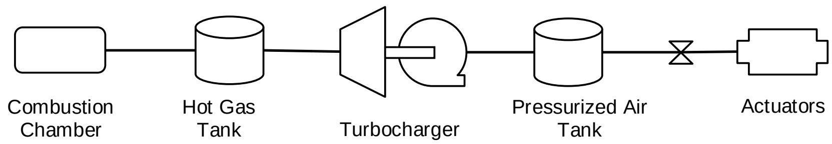

Figure 5 – Turbocharger system

- *Turbocharger* is a device where the combustion gases are used to drive a turbine, which powers a compressor to provide pressurized air for the actuators, as sketched in Fig. 5. A search for commercial models was carried out, most among automotive models, which work in a lower temperature (900ºC), making necessary the use a cooling system. In Fig. 6 can be seen flow x pressure ratio chart for the compressor (left) and for the turbine (right) of the GT12 turbocharger model from Garrett®.

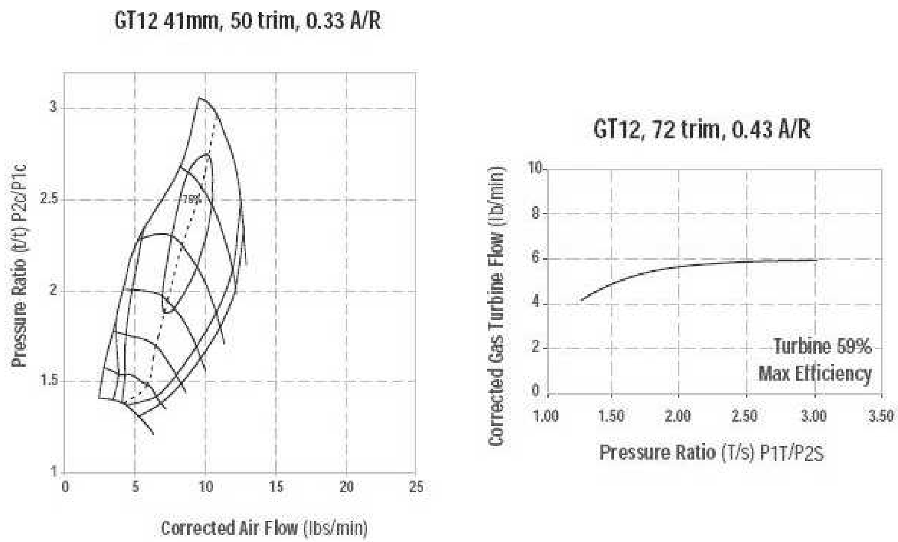

Figure 6 - Flow x Pressure Ratio charts for compressor (left) and turbine (right) from GT12 Garret®

The GT12 model is the commercial turbocharger that most closely fits the requirements of the project. The compressor may deliver pressured air at 3 bar, with a flow of 11 lbs/min (83.16 g/s). Using the average molar mass of air as 28.96 g/mol and considering it as an ideal gas, the volumetric flow is 23.9×10^{-3} m^3/s. As the volume change for a contraction cycle is 0.85×10^{-3} m^3, the flow delivered by the compressor would supply enough pressured air for the robot, so the compressor is appropriated. Besides, to work at its maximum efficiency, the turbine needs a flow of 6 lb/min (45.3 g/s), that means, a mass of 2,72 kg/min of propellant. That, together with the fact that a cooling system for the turbine is necessary, would make the whole propulsion system too heavy, becoming the project infeasible.

- *Expandable Combustion Chamber*: here the combustion chamber has a variable volume, like an automotive piston-cylinder assembly. From the set of equations in Eq. 5, the deliverable work of such assembly may be calculated if some simplifications are considered (Barbosa, M.P.A., 2000). First, the combustion gases are considered as ideal, whose thermodynamic properties are close enough to air properties. Second, the combustion and the simultaneous expansion are substituted by the propellant burned at constant volume followed by an adiabatic expansion.

$$\begin{aligned} P_2 &= P_1 \cdot \left(V_1 / V_2 \right)^{\gamma} \\ T_2 &= T_1 \cdot \left(P_1 / P_2 \right)^{\frac{1-\gamma}{\gamma}} \\ W &= \frac{1}{1-\gamma} \cdot \left(P_2 \cdot V_2 - P_1 \cdot V_1 \right) \end{aligned} \tag{5}$$

Consider the propellant molar mass as 243 g/mol and the chamber volume as 1000 mm^3. Given the combustion temperature and grain mass, it is possible to calculate the pressure P_1 after combustion equal to 441 bar. For an exhaust with positive pressure P_2 (the pressure at the end of the expansion), the pressure is set equal to 2 bar. That will result in an exhaust temperature T_2 equal to 276.7^{o}C and a deliverable work W equal to 86.7 J. The dispenser adopted enables 180 shots/min in machine guns, what leads to a available power of 260.1 W.

This assembly will drive a compressor which usually demands 120W to deliver a flow of $1.69x10^{-5}$ m^3/s of pressured air at 18 bar, but using all the available power, it can deliver $2.20x10^{-4}$ m^3/s at 3 bar. As already stated, the volume for a step (a contraction cycle) is $5.02x10^{-4}$ m^3 at 3 bar; therefore, the robot would take 0.44 s for a step, thus running at 2.58 m/s.

4. CONCLUSIONS

Three different systems were briefly analyzed: the expansion valve, the turbo charger and the expandable chamber. The first system doesn't seem to be a good solution because of its very low efficiency, as the second one couldn't be easily implemented.

The expandable chamber enables a reasonably high speed, what is very promising, since all the calculations were carried out in a first trial to fit commercial parts. Now, a more complete simulation has to be carried out in order to obtain more exact values to set the parameters to construct a prototype.

Special attention has to be paid to the temperatures of the gas generator and the exhaustion gases, to avoid degradation of the system performance and for its safety as well.

5. ACKNOWLEDGEMENTS

This work is financially supported by the "National Counsel of Technological and Scientific Development".

6. REFERENCES

Army Science Conference. "Accelerating the pace of transformation to the objective force". Baltimore, 2000. 1 CD-ROM.

Barbosa, M.P.A.; Desenvolvimento de Sistemas Base-Bleed para granadas HE de Obuseiros 155mm. Instituto Militar de Engenharia. IME. Rio de Janeiro. RJ – BR. Fevereiro de 2000 a novembro de 2000.

Barth, E.J., Gogola, M.A, Goldfarb, M. "Modeling and Control of a Monopropellant-Based Pneumatic Actuation System". Proceedings of the 1003 IEEE International Conference 00 Robotics &Automation Taipei, Taiwan, September 14-19,2003.

Bittencourt, G.A.; Bandeira, E.L.; Mapeamento da Velocidade de Boca de uma Munição 9mm Utilizando Lógica Fuzzy. Instituto Militar de Engenharia. IME. Rio de Janeiro. RJ – BR. Fevereiro de 2001 a novembro de 2001.

Dunningan, James F. "Digital Soldiers: the evolution of high-tech weaponry and tomorrow's brave new battlefield". USA, october 1996.

Greenwood, D.T. "Classical Dynamics". Dover Publications. NY – USA. 1977.

Hiller, M.; Germann, D.; Morgado de Gois, J. A.; Design and control of a quadruped robot walking in unstructured terrain. IEEE Conference on Control Applications, CCA 2004, Taipei, Taiwan, 2004.

Morgado de Gois, J.A.; Design and energetic characterization of a solid-propellant self-powered robot. XII International Symposium on Dynamic Problems of Mechanics – DINAME 2007, Ilha Bela, Brasil.

Morgado de Gois, J. A.; Hiller, M.; Ultrasound sensor system with Fuzzy data processing. 7th International Conference on Climbing and Walking Robots CLAWAR 2004, Madrid, Spain, 2004.

Morgado De Gois, J.A.; Germann, D.; Hiller, M.; Sensor-based Ground Detection in unstructured Terrain for the walking machine ALDURO, 6th International Conference on Climbing and Walking Robots – CLAWAR, Catania, Italien, 17.-19. September, 2003

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.