Control architecture of LUCY, a Biped with Pneumatic Artificial Muscles

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Summary. This paper describes the biped Lucy and it's control architecture that will be used. Lucy is actuated by Pleated Pneumatic Artificial Muscles, which have a very high power to weight ratio and an inherent adaptable compliance. These characteristics will be used to let Lucy walk in a dynamically stable manner while exploiting the adaptable passive behaviour of these muscles. A quasi-static global control has been implemented while using adapted PID techniques for the local feedback joint control. These initial control techniques resulted in the first movements of Lucy. This paper will discuss a future control architecture of Lucy to induce faster and smoother motion. The proposed control scheme is a combination of a global trajectory planner and a local low-level joint controller. The trajectory planner generates motion patterns based on two specific concepts, being the use of objective locomotion parameters, and exploiting the natural upper body dynamics by manipulating the angular momentum equation. The low-level controller can be divided in four parts: a computed torque module, an inverse delta-p unit, a local PI controller and a bang-bang controller. In order to evaluate the proposed control structure a hybrid simulator was created. Both the pneumatics and mechanics are put together in this hybrid dynamic simulation.

1 Introduction

Most of the legged robots nowadays use electrical drives. Well know robots are Asimo[1], Qrio[2], Johnnie[3] and HRP-2P[4]. Because the torquedensity of the drives is too low to actuate legs, gearboxes are used to deliver the required torque at low rotation speeds, thereby making the joint stiff and losing joint compliance. While the compliance characteristics actually can be beneficial for legged locomotion to reduce shocks and decrease energy consumption.

The research group Multibody Mechanics of the Vrije Universiteit Brussel has built the planar walking biped Lucy. This biped model is actuated by pleated pneumatic artificial muscles (PPAM)[5]. These actuators are an alternative to the McKibben type muscle by trying to overcome some of the latter's shortcomings such as a high threshold of pressure and dry friction. The goal of the biped project is to achieve a lightweight bipedal robot able to walk in a dynamically stable way while exploiting the passive behaviour of the pleated pneumatic artificial muscles in order to reduce energy consumption and control effort. Presently Lucy has been assembled and tested. A picture of the complete set-up is given in figure 1. The movement of Lucy is restricted to the sagittal plane by a sliding mechanism. The structure is made of a high-grade aluminium alloy, AlSiMg1, and is composed of two legs and an upper body. The robot, all included, weighs about $30kg$ and is $150cm$ tall. The robot has 12 pneumatic actuators for 6 DOF's.

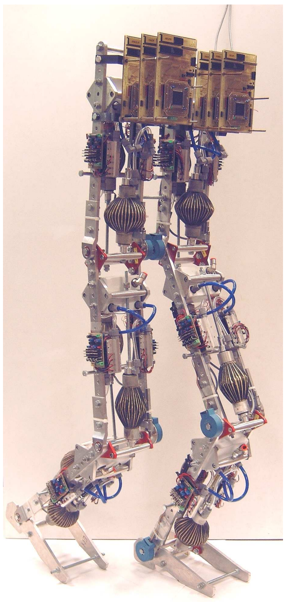

Fig. 1. Photograph of Lucy

Fig. 2. Photograph of deflated and inflated state of the PPAM

2 Control Architecture

Presently Lucy has been assembled and debugged, here basic control strategies were implemented. With basic PID techniques already satisfactory behaviour was attained[6]. The following step will be the implementation of a dynamic control scheme to induce faster and smoother motion. An overview of this control architecture is given in the next paragraphs. In order to evaluate the proposed control structure an hybrid simulator was created, which means that both the pneumatics and mechanics are put together in a dynamic simulation. The pressure building inside the muscle is represented by first order differential equations deduced from the first law of thermodynamics for an open system while assuming a perfect gas for the compressed air. The orifice valve flows are derived from the model presented by ISO635[7]. The integration of these first order differential equations coupled with the mechanical differential equations gives the torques.

The considered controller is given in the schematic overview of figure 3 and is a combination of a global trajectory planner and a local low-level joint controller. The low-level controller can be divided in four parts: the computed torque module, the inverse Δp unit, the local PI controller and the bang-bang controller. The implementation of the trajectory planner, computed torque module and inverse Δp control is done in a central computer, working with a refresh rate of 500Hz. Each joint is controlled with a micro-controller working at 2000Hz and is used for the local PI controller and bang-bang controller. The communication system uses the USB 2.0 protocol.

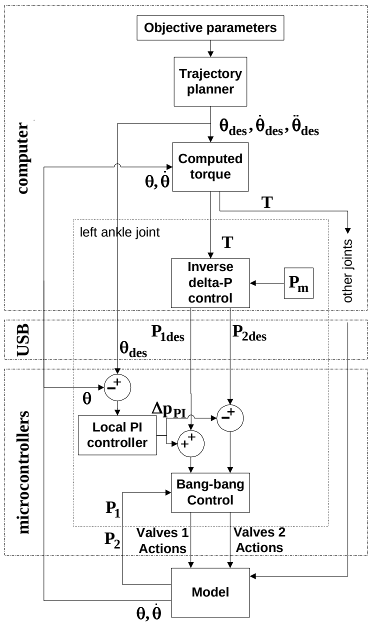

Fig. 3. The applied control architecture

2.1 Trajectory Planning

The trajectory planner generates motion patterns based on two specific concepts, being the use of objective locomotion parameters, and exploiting the natural upper body dynamics by manipulating the angular momentum equation [8]. The trajectories of the leg links, represented by polynomials, are planned in such a way that the upper body motion is naturally steered, meaning that in theory no ankle torque would be required. To overcome possible external disturbances, a polynomial reference trajectory is established for the upper body motion, which mimics a natural trajectory. Consequently the required ankle torque is low, meaning that it does not cause the Zero Moment Point[9] to move out of the predefined stability region. One of the most interesting aspects of this method is that they are based on fast converging iteration loops, requiring only a limited number of elementary calculations. The computation time needed for generating feasible trajectories is low, which makes this strategy useful for real-time applications.

2.2 Complete Low-level Joint Controller

Computed Torque Using the Lagrange equations of the dynamic model the equations of motion can be summarized in the following matrix form (during single support):

$$M(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + G(\theta) = T$$

Where M is the inertia matrix, which is symmetric and positive definite, C is the centrifugal matrix which contains the centrifugal forces (involving $\dot{\theta}_i^2$) and the coriolis forces (involving $\dot{\theta}_i\dot{\theta}_j$ for $i \neq j$), G is the gravitational force vector. This is the feedforward calculation which is added with a proportional and derivative feedback part for which the gains are tuned in order for the mechanical system to behave as critically damped.

During the double support phase, immediately after the impact of the swing leg, three geometrical constraints are enforced on the motion of the system. They include the stepheight, steplength and angular position of the foot. Due to these constraints, the robot's number of DOF is reduced to three.

The equations of motion are then written as

$$M(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + G(\theta) = T + J^T\Lambda$$

where J is the Jacobian matrix and Λ is a column vector of Lagrange multipliers representing the generalized constraint forces. An extra equation is introduced to force the ankle torques to zero as proposed by the trajectory planner. This problem can be solved by dividing the 6 coordinates into a group of independent and dependent coordinates. Using the matrix pseudoinverse as described in [10], the torque vector can than be calculated. This feedforward term is added with a feedback part similar as in single support which gives the computed torque.

Inverse Δp Control For each joint a computed torque is available. The computed torque is then feeded into the inverse delta-p control unit, one for each joint, which calculates the required pressure values to be set in the muscles. The generated torque in an antagonistic setup with two muscles is:

$$T = T_1 - T_2 = p_1 l_1^2 r_1 f_1 - p_2 l_2^2 r_2 f_2$$
$$= p_1 t_1 (\theta) - p_2 t_2 (\theta) \tag{1}$$

with p_1 and p_2 the applied gauge pressures in extensor and flexor muscle respectively which have lengths l_1 and l_2. The dimensionless force functions of both muscles are given by f_1 and f_2. The kinematical transformation from forces to torques are represented by r_1 and r_2 which results, together with the muscle force characteristics, in the torque functions t_1 and t_2. These functions are determined by the choices made during the design phase and depend on the joint angle θ. Thus joint position is influenced by weighted differences in gauge pressures of both muscles.

The two desired pressures are generated from a mean pressure value p_m while adding and subtracting a Δp value:

$$p_{1des} = p_m + \Delta p \tag{2}$$
$$p_{2des} = p_m - \Delta p \tag{3}$$

The mean value p_m will determine the joint stiffness and will be controlled in order to influence the natural dynamics of the system. Feeding back the joint angle θ and using expression (1), Δp can be determined by:

$$\Delta p = \frac{T + p_m \left((t_2 (\theta) - t_1 (\theta) \right)}{t_2 (\theta) + t_1 (\theta)} \tag{4}$$

The delta-p unit is thus a feed-forward calculation from torque level to pressure level using the kinematic model of the muscle actuation system.

Local PI Controller Because the communicationspeed between PC and the micro-controllers is $2ms$, instabilities occur when the proportional and derivative feedback part of the computed torque are too high. To track the desired trajectory a local PI controller was needed to regulate the error introduced by lowering the feedback gains.

Bang-bang Controller In order to realize a lightweight, rapid and accurate pressure control, fast switching on-off valves are used. The pneumatic solenoid valve 821 2/2 NC made by Matrix weighs only $25g$. The opening time is about 1 ms and it has a flow rate of 180 Std.l/ min. A set of 2 inlet and 4 outlet valves are used per muscle. In the last control block the desired gauge pressures are compared with the measured gauge pressure values after which appropriate valve actions are taken by the bang-bang pressure controller (see figure 4).

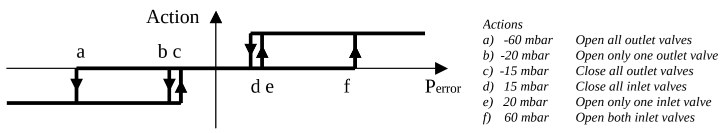

Fig. 4. Multi-level bang-bang control scheme

2.3 Results

The following values for the objective parameters characterize the walking pattern:

$\nu = 0.2\frac{m}{s} = 0,72\frac{km}{h}$	walking speed	$\delta = 0m$	stepheight
$\lambda = 0.15m$	steplength	$\gamma = 0.02m$	footlift

The walking motion is considered to be a steady walking pattern, consisting of successive single support phases separated by a double support phase. The duration of the double support phase will be chosen as 20% of the total step duration, corresponding to its duration in human walking at low speeds [11]. So the duration of one step becomes $0.74s$.

The model parameter uncertainties are 5% on the mass and COG and 10% on the inertia. The simulations take a time delay of $1ms$ for the closing and opening of the valves into account. The sampling time for the calculation of the desired pressures is $2ms$, which is restricted due to the communication between PC and micro-controller. The local PI controller and bang-bang controller, both implemented in the micro-controllers, work with a refresh rate of $0.5ms$.

Figures 7 and 8, representing respectively the pressures and valve actions of the front and back muscle of the knee of the left leg, clearly shows the control strategy of keeping the mean pressure constant, which in this case is set at a value of $2bar$. Also the valve action due to the bang-bang controller is shown. Note that in these figures a closed valve is represented by a horizontal line at $2bar$ while a peak upwards represents one or more opened inlet valves, a peak downwards one or more opened exhaust valve. The selection of an appropriate mean pressure value is important regarding energy consumption and control activity. Future work will be the incorporation of this mean pressure value determination in a higher-level control strategy.

The pressures of the front and rear muscles determines the torques (figure 6). Notify the very small ankle torques. The difference between desired and real angle (for example figure 5, giving the angle results for the ankle of the supporting leg) never exceeds the $0.1°$. For biped locomotion this tracking error is not a problem if the overall stability of the robot is not threatened.

Indication of postural stability is given by the ZMP shown in figure 9. One can verify that during the single support phase the ZMP remains close to the ankle joint. During the double support phase the ZMP is transferred from the rear ankle joint to the front ankle joint. This can be seen in figure 10 where the weight shift from the rear foot to the front foot is clearly visible.

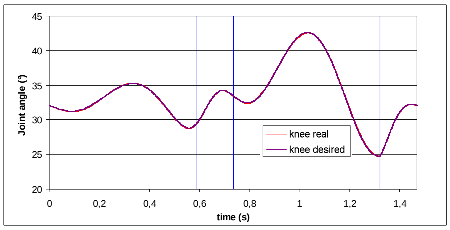

Fig. 5. knee angle of left leg

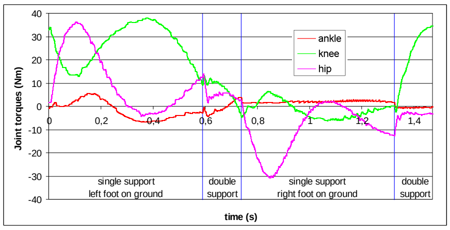

Fig. 6. torques of left leg

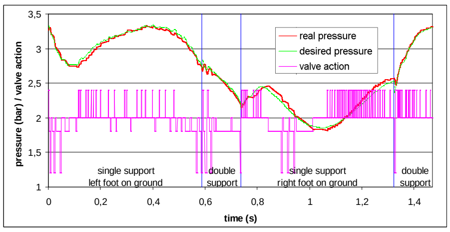

Fig. 7. pressure and valve action of front knee muscle of left leg

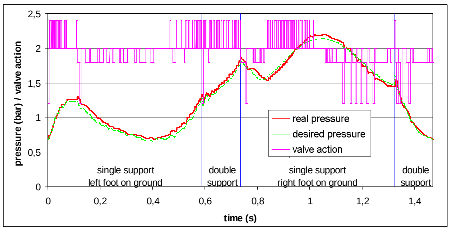

Fig. 8. pressure and valve action of back knee muscle of left leg

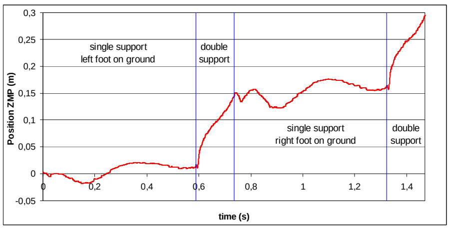

Fig. 9. Zero moment point position

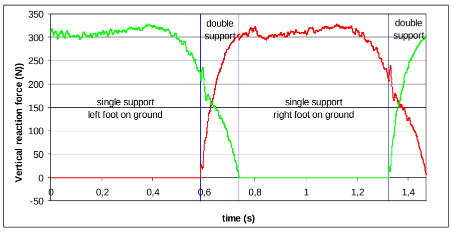

Fig. 10. Vertical ground reaction forces

3 Conclusion

A Pleated Pneumatic Artificial Muscle is very suitable to power a smooth walking bipedal robot. This actuator has a high power to weight ratio and an inherent adaptable passive behaviour. Two antagonistically coupled muscles can be implemented in a straightforward manner to power a rotative joint. The angular position of such a rotative joint depends on the difference in gauge pressures of both muscles and the stiffness of the joint is determined by the sum of pressures. Thus stiffness can be controlled while changing angular position. The biped Lucy is a robot actuated with these muscles.

A future control architecture, based on a global and local control, was discussed and tested in hybrid simulation. A global control is the trajectory planner for dynamically balanced bipeds, the local control can be divided in four parts: a computed torque module, an inverse delta-p unit, a local PI controller and a bang-bang controller.

The simulations showed already promising results. The next step will be the incorporation of this control architecture in the real bipedal robot Lucy.

Acknowledgments

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References

1. K. Hirai, M. Hirose, Y. Haikawa, and T. Takenaka, , “The development of honda homanoid robot,” *IEEE International Conference on Robotics and Automation*, Leuven, Belgium, pp. 1321–1326, 1998.
2. Sony-PressRelease, “World’s first running humanoid robot,” December 18th 2003.
3. F. Pfeiffer, K. Löffler, and M. Gienger, “Sensor and control aspects of biped robot ”Johnnie”,” *IEEE International Conference on Humanoid Robots*, Munich, Germany,2003.
4. K. Yokoi and al., “Humanoid robot’s applications in HRP,” in IEEE International Conference on Humanoid Robots” *IEEE International Conference on Humanoid Robots*, Karlsruhe, Germany, 2003.
5. F. Daerden and D. Lefeber, “The concept and design of pleated pneumatic artificial muscles,” *International Journal of Fluid Power*, vol. 2, no. 3, pp. 41–50, 2001.
6. R. Van Ham,B. Verrelst,B. Vanderborght,F. Daerden and D. Lefeber, “Experimental results on the first movements of the pneumatic biped ”Lucy”,” *6th International conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines*, Catania, Italy, pp. 485–492, 2003.
7. ISO6358, “Pneumatic fluid power - method of test - determination of flow rate characteristics of components using compressible fluids,” 1989.
8. J. Vermeulen, *Trajectory Generation for Planar Hopping and Walking Robots: An Objective Parameter and Angular Momentum Approach,* PhD Dissertation, Vrije Universiteit Brussel, April 2004.
9. M. Vukobratović and B. Borovac, “Zero-moment point – Thirty years of its life,” *Int. Journal of Humanoid Robotics*,vol. 1, pp. 157–173, 2004.
10. C.L. Shih and W. Gruver, “Control of a Biped Robot in the Double-Support Phase,” *IEEE Trans. on Systems, Man, and Cybernetics*,vol. 22(4), pp. 729–35, 1992.
11. M. Hardt, K. Kreutz-Delgado, J. Helton and O.V. Stryk, “ Obtaining minimum energy biped walking gaits with symbolic models and numerical optimal control,” *Workshop - Biomechanics Meets Robotics, Modelling and Simulation of Motion*, HeidelBerg, Germany, pp. 1–19, 1999