A strategy to combine active trajectory control with the exploitation of the natural dynamics to reduce energy consumption for bipedal robots

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Abstract—The biped Lucy, powered by pleated pneumatic artificial muscles, has been built and controlled and is able to walk up to a speed of $0.15 m/s$. The pressures inside the muscles are controlled by a joint trajectory tracking controller to track the desired joint trajectories calculated by a trajectory generator. However, the actuators are set to a fixed stiffness value. In this paper a compliance controller is proposed which can be added in the control architecture to reduce the energy consumption by exploiting the natural dynamics. The goal of this research is to preserve the versatility of actively controlled humanoids, while reducing their energy consumption. A mathematical formulation has been developed to find an optimal stiffness setting depending on the desired trajectory and physical properties of the system and the proposed strategy has been validated on a pendulum structure powered by artificial muscles. This strategy has not been implemented on the real robot because the walking speed of the robot is currently too slow to benefit already from compliance control.

I. INTRODUCTION

Many research is currently going on to improve the capabilities of humanoid robots. An important part is the locomotion issue. Although bipedal locomotion is expected to have higher mobility compared to wheeled robots, the walking capabilities are still limited. Ongoing research in this field is performed by for example Michel et al. to walk among obstacles [1], Verrelst et al. to step over obstacles [2], Hirukawa et al. to check stability when also hands are used in contact with the environment [3] and Yoshida et al. to manipulate objects while walking [4]. Another important issue is the power consumption. The continuous operating time of for example Asimo is 1 hour [5]. In order to ever be useful in a real application the autonomy must definitely increase. This can be done by developing better power sources (e.g. batteries) and increasing the efficiency of walking. Limit cycle walkers are well known for their energy efficiency. The energetic cost (amount of energy used per meter traveled per unit of weight) of these robots is between one and two orders of magnitude smaller than the energetic cost of actively controlled humanoids [6]. Unfortunately they are of little practical use: they cannot start and stop autonomously and they cannot change their gait due to the fixed dynamics. This is in contrast with the actively controlled bipeds as for example Asimo and HRP-2. They use precise joint-angle control and are consequently very versatile. The optimum is probably somewhere in between the active and passive walkers as shown in figure 1: a combination of active control to be able to perform different tasks with exploiting the passive dynamics to reduce energy consumption. On the right hand side of figure 1 are the limit cycle walkers. By adding compliant actuation in the hip (Mike [7]) or ankle [8] the passive walkers are able to walk over level ground. By changing the compliance the robots are able to walk at different walking speeds (Veronica [9] and Dribbel [10]). On the left hand side of figure 1 are the trajectory controlled robots, usually the stability is checked based on the Zero Moment Point (ZMP). Using compliant actuators the robots are able to exploit the natural dynamics and reduce the energy consumption. Experiments with the walking robot WL-14 showed a reduction of 25% of energy consumption during the swing phase when the compliance was controlled, compared to the case when the stiffness was not varied actively [11]. This was measured when walking at $1.28 \text{s/step}$ and $0.15 m/\text{step}$. Strategies on how the optimal stiffness was chosen were not discussed. The goal of the Lucy-project is to develop a control strategy which is a combination of calculating dynamic stable trajectories for the different joint links which are tracked by actively controlling the actuators in the different joints and a compliance controller to reduce the energy consumption. Essential for this research is the use of adaptable compliant actuators so the natural dynamics of the system can be controlled. An interesting actuator, introducing such compliance for robotic mechanisms, is the pleated pneumatic artificial muscle (PPAM), because in an antagonistic setup both the torque and the compliance of the joint can be controlled.

The developed control strategy is evaluated on a pendulum structure powered by PPAMs (figure 3). The design is exactly the same as a limb of the robot Lucy (figure 2). A pendulum is chosen because walking is often modeled as the motion of two coupled pendula: the stance leg behaves like an inverted pendulum moving about the stance foot and the swing leg like a regular pendulum swinging about the hip [12]. The start of this research was published in [13], where only sinusoidal functions were discussed, here the strategy is extended to all possible trajectories.
II. PENDULUM POWERED BY PPAMS

The complete pendulum set-up is shown in figure 3. The physical properties of the pendulum are:

- Length of the link: $l = 0.45m$
- Coefficient denoting COG from rotation point: $\alpha = 0.77$
- Mass: $m = 6.81kg$
- Inertia in COG: $I = 0.1105kgm^2$

The sensors are an Agilent HEDM6540 incremental encoder for reading the joint position and two pressure sensors (Honeywell CPC100AFC), mounted inside each muscle. The controller is implemented on a PC and 2 data acquisition cards of National Instruments are used. The NI PCI-6602 Counter/Timer with 8 up/down, 32-bit counter/timers is used to measure the joint angles and a NI PCI-6220 with 16 analog inputs and 24 digital I/O are used to control the valves, measure the pressures and joint velocity. Both PC cards are unable to measure the angular velocity out of the encoder signal, so a PIC16F876A micro-controller, working at $2MHz$ is used to measure the time between the pulses and detect the sign. The velocity signal is sent as an analog signal to the data acquisition card. The airmass consumption is measured by a compressed air meter SD6000 of IFM Electronics.

A. Antagonistic joint powered by Pleated Pneumatic Artificial Muscles

A pneumatic artificial muscle is essentially a membrane that expands radially and contracts axially when inflated, while generating high pulling forces along the longitudinal axis. The force generated by a muscle is (for detailed equations see [13]):

$$ F = pl^2f\left(\epsilon, \frac{l}{R}\right) $$  \hspace{1cm} (1)

where $p$ is the applied gauge pressure, $l$ the muscle’s full length, $R$ its unloaded radius and $\epsilon$ the contraction. The dimensionless force function $f$ depends only on contraction and geometry.

Pneumatic artificial muscles can only pull. In order to have a bidirectionally working revolute joint one has to couple two muscles antagonistically. Taking into account equation (1) and if $r_1$ and $r_2$ define the lever arm of the agonist and antagonist muscle respectively, the joint torque is given by following expression

$$ T = T_1 - T_2 = p_1l_1^2r_1f_1 - p_2l_2^2r_2f_2 = p_1f_1(\theta) - p_2f_2(\theta) $$  \hspace{1cm} (2)

with $p_1$ and $p_2$ the applied gauge pressures in the agonist and antagonist muscles respectively having lengths $l_1$ and $l_2$. The dimensionless force functions of both muscles are given by $f_1$ and $f_2$.

Due to the gas compressibility the muscle is compliant. Joint stiffness, the inverse of compliance, for the considered revolute joint can be obtained by the angular derivative of the torque characteristic in equation (2):

$$ K = \frac{dT}{d\theta} = \frac{dT_1}{d\theta} - \frac{dT_2}{d\theta} = \frac{dp_1}{d\theta}t_1 + p_1\frac{dt_1}{d\theta} - \frac{dp_2}{d\theta}t_2 - p_2\frac{dt_2}{d\theta} $$  \hspace{1cm} (3)

The terms $dp_i/d\theta$ represent the share in stiffness of changing pressure with contraction, which is determined by the action of the valves controlling the joint and by the thermodynamical processes. If polytropic compression/expansion with closed valves is assumed, then the pressure changes inside the muscle will be a function of volume changes:

$$ P_iV_i^n = P_{o_i}V_{o_i}^n $$  \hspace{1cm} (4)

with:

$$ P_i = P_{atm} + p_i $$  \hspace{1cm} (5)

leading to:

$$ \frac{dp_i}{d\theta} = -n(P_{atm} + p_i)\frac{V_{o_i}^n}{V_i^{n+1}} \frac{dV_i}{d\theta} $$  \hspace{1cm} (6)

with $P_i, V_i$ the absolute pressure and volume of muscle $i$, $P_{o_i}$ the absolute initial pressure, $V_{o_i}$ the initial volume when the valves of muscle $i$ were closed and $p_i, p_{o_i}$ the gauge pressure and initial gauge pressure. $n$ is the polytropic index and $P_{atm}$ the atmospheric pressure.
Taking the torque characteristics as an example the following reasoning can be made for muscles with closed valves. An increase of the angle \( \theta \) will result in an increase of the torque generated by the agonistic muscle while its volume will decrease. Thus \( dt_1/d\theta > 0 \) and \( dV_1/d\theta < 0 \). For the antagonistic muscle the actions will be opposite. Combining equation (3), (4) and (6) with this information gives:

\[
K = (k_1p_{1,n} + k_2p_{2,n} + k_{atm} P_{atm})
\]

with:
\[
k_1 = t_1 n \frac{V_1^n}{V_1^{n+1}} \left| \frac{dV_1}{d\theta} \right| + \frac{V_1^n}{V_1^{n+1}} \left| \frac{dt_1}{d\theta} \right| > 0
\]
\[
k_2 = t_2 n \frac{V_2^n}{V_2^{n+1}} \left| \frac{dV_2}{d\theta} \right| + \frac{V_2^n}{V_2^{n+1}} \left| \frac{dt_2}{d\theta} \right| > 0
\]
\[
k_{atm} = k_1 + k_2 - \left| \frac{dt_1}{d\theta} \right| - \left| \frac{dt_2}{d\theta} \right|
\]

The coefficients \( k_1, k_2, k_{atm} \) are a function of the joint angle and are determined by the joint and muscles geometry. From equation (7) the conclusion is drawn that a passive spring element is created with an adaptable stiffness controlled by the weighted sum of both initial gauge pressures when closing the muscle.

Since stiffness depends on a sum of gauge pressures while position is determined by differences in gauge pressure, the angular position can be controlled while setting stiffness.

**B. Control architecture**

The control architecture is similar as the one used for the biped Lucy (see [14]) and is depicted in figure 4. The tracking controller consists of a computed torque controller, a delta-p unit and a pressure bang-bang controller. The computed torque controller calculates the required joint torque. In this unit the computed torque technique consists of a feedforward part and a PID feedback loop is implemented. The delta-p unit translates these calculated torques into desired pressure levels for the two muscles of the antagonistic set-up. These two pressures are generated as follows:

\[
\dot{p}_1 = \dot{p}_s \left( \frac{\dot{\theta}}{t_1(\theta)} \right) + \Delta \ddot{p}
\]
\[
\dot{p}_2 = \dot{p}_s \left( \frac{\dot{\theta}}{t_2(\theta)} \right) - \Delta \ddot{p}
\]

with \( \dot{p}_s \) a parameter that is used to control the sum of pressures and consequently the joint stiffness and \( \Delta \ddot{p} \) a parameter that controls the difference in pressure of the two muscles in order to control the generated torque. Feeding back the joint angle \( \theta \) and using expression (2), \( \Delta \ddot{p} \) can be determined by:

\[
\Delta \ddot{p} = \frac{T}{t_1(\theta) + t_2(\theta)}
\]

The delta-p unit is thus a feed-forward calculation from torque level to pressure level and uses estimated values of the muscle force function and estimated kinematical data of the pull rod mechanism.

When the equation (6) is substituted in equation (3), while using the required pressures (equation (8)) for substituting \( p_i \), then \( \dot{p}_s \) is derived as a function of the desired stiffness \( K \).

\[
\dot{p}_s = \frac{K - g_1 \Delta \ddot{p} - g_2}{g_3}
\]

with
\[
g_1(\dot{\theta}, \dot{\theta}) = (\frac{nt_1}{V_1} \frac{dV_1}{d\theta} + \frac{nt_2}{V_2} \frac{dV_2}{d\theta} + \frac{dt_1}{d\theta} + \frac{dt_2}{d\theta})
\]
\[
g_2(\dot{\theta}, \dot{\theta}) = P_{atm}(\frac{nt_1}{V_1} \frac{dV_1}{d\theta} + \frac{nt_2}{V_2} \frac{dV_2}{d\theta})
\]
\[
g_3(\dot{\theta}, \dot{\theta}) = (\frac{n}{V_1} \frac{dV_1}{d\theta} + \frac{n}{V_2} \frac{dV_2}{d\theta} + \frac{dt_1}{d\theta} - \frac{1}{t_2} \frac{dt_2}{d\theta})
\]

Each time the controller calculates new pressures, an adaptation of \( \dot{p}_s \) should be made in order to control the compliance. The control of the compliance is consequently a feedforward calculation.

The biped has for each muscle a valve island consisting of 2 inlet and 4 outlet on-off valves instead of the heavy proportional valves. So also the pendulum has valve islands. 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 multi-level bang-bang pressure controller with dead zone.

**III. EXPERIMENTAL RESULTS FOR SINUSOIDAL TRAJECTORIES**

In a first real experiment the desired trajectory is a sine wave at a certain frequency and amplitude. The experiments have been repeated for different stiffness settings. Figure 5 shows the total measured average airmass consumption over 5 swing motions as a function of the stiffness and frequency for sinusoidal trajectories with an amplitude of 10°. The frequency ranges from 1.5 Hz to 2.5 Hz, in steps of 0.1 Hz, the stiffness
goes from $50\text{Nm/rad}$ to $150\text{Nm/rad}$ in steps of $5\text{Nm/rad}$. The stiffness is limited because of the minimum and maximum pressure inside the muscles. At higher and lower stiffness settings the required torques cannot be generated anymore and the tracking performance deteriorates. This can be seen in equation (8). $\Delta p$ has a certain range to attain the desired torque, consequently $p_s$ is limited. It is clear that there exists an optimal stiffness value and it is logical that for increasing frequencies the optimal stiffness will increase as well.

Another important factor influencing the airmass consumption is the dead volume in the muscle and tubing. This volume has to be pressurized and depressurized without contributing to the output force. So the tubes should be taken as short as possible, thus the valve system should be placed close to the muscle. Another improvement is to add material in the muscles to reduce the dead volume. Davis et al. [15] experimented with different filler materials which gave a higher bandwidth and reduced air consumption.

### IV. Compliance control

The previous experiments showed that each time an optimal compliance could be found for which the airmass consumption was minimal. This optimal compliance is dependent of the imposed trajectory and the physical properties of the pendulum.

The idea behind the compliance controller is to fit the actuator compliance to the natural compliance of the desired trajectory. The natural stiffness of the desired trajectory $K_{\text{trajectory}}$, the inverse of the compliance, is calculated as the derivative of the torque $\dot{T}$ necessary to track the desired trajectory with respect to the joint angle $\dot{\theta}$. The torque $\dot{T}$ is given by the inverse dynamics:

$$K_{\text{trajectory}} = \frac{d\ddot{T}}{d\ddot{\theta}} = \frac{d}{d\ddot{\theta}} (\dot{D}(\ddot{\theta})\ddot{\theta} + \dot{C}(\ddot{\theta}, \ddot{\theta}) + \ddot{G}(\ddot{\theta}))$$  

(11)

where $\dot{D}$ is the inertia matrix, $\dot{C}$ is the centrifugal and coriolis term and $\ddot{G}$ is the gravity term, all of these containing estimated values. $\ddot{\theta}$ is the desired trajectory. This stiffness $K_{\text{trajectory}}$ is substituted in equation (10) as a value for $K$. This is a major change over strategies where an arbitrary compliance value is taken as is the case with most of the robots powered by pneumatic muscles [16], [17].

For a pendulum the optimal stiffness $K_{\text{trajectory}}$ becomes:

$$K_{\text{trajectory}} = \frac{d\ddot{T}}{d\ddot{\theta}} = \frac{d}{d\ddot{\theta}} (d_{11}\ddot{\theta} + g_1 \sin(\ddot{\theta}))$$

(12)

with $d_{11} = ma^3l^2 + I = 0.92\text{kgm}^2$ and $g_1 = g\alpha l = 23.45\text{Nm}$ for this pendulum.

For a sinusoidal trajectory $\ddot{\theta} = A\sin(\omega t)$, the optimal stiffness becomes:

$$K_{\text{trajectory}} = d_{11} - A\omega^3\cos(\omega t)$$

(13a)

$$= -d_{11}\omega^2 + g_1 \cos(A\sin(\omega t))$$

(13b)

$$\approx -d_{11}\omega^2 + g_1$$

(13c)

with $A$ the amplitude of the motion, $\omega = 2\pi f$ the angular frequency and $f$ the frequency. The approximation of equation (13c) is valid if $\ddot{\theta}$ is small. So the optimal stiffness approximates a constant value dependent on the physical properties of the pendulum and the frequency of the imposed motion in case $\ddot{\theta}$ is small.

Table I gives the experimentally determined stiffness $K_{\text{exp}}$ and the calculated natural stiffness of the desired trajectory $K_{\text{trajectory}}$ for different frequencies. One can conclude that the calculated stiffness gives a good approximation of the stiffness that is needed in order to reduce airmass consumption. The stiffness of the trajectory $K_{\text{trajectory}}$ can thus be considered as the optimal stiffness, so $K_{\text{opt}} = K_{\text{trajectory}}$. At frequencies above $2.2Hz$ the optimal stiffness is outside the range the muscles can cover.

<table>
<thead>
<tr>
<th>Sine wave frequency (Hz)</th>
<th>$K_{\text{trajectory}}$ (Nm/rad)</th>
<th>$K_{\text{opt}}$ (Nm/rad) amplitude = $5^\circ$</th>
<th>$K_{\text{opt}}$ (Nm/rad) amplitude = $10^\circ$</th>
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| TABLE I | EXPERIMENTAL AND CALCULATED OPTIMAL VALUES OF $K_{\text{opt}}$ |
V. NON-NATURAL TRAJECTORIES

In the previous section it was found that the optimal stiffness $K_{opt}$ for a sinusoidal function is the derivative of the torque $\tilde{T}$ with respect to the joint angle $\theta$ and that this approximates a constant value. This value can be visualized in a torque-angle graph which for a sine function is a straight line under a certain angle. The slope represents the stiffness. This is shown for different frequencies in figure 6. At low frequencies (e.g. $0.5Hz$) the slope of this curve is positive, the actuator has to generate a positive torque for positive angles to decelerate the pendulum. Reason is that the desired motion is slower than the natural motion. Adapting the stiffness is not valuable here because stiffness can only increase the natural frequency. When the frequency increases the slope of the swing period becomes negative and stiffness adaptation can be used to exploit the natural dynamics.

![Fig. 6. Torque-angle relation for sinusoidal trajectory for different frequencies](image)

For more complex trajectories than a sine function, equation (12) for $K_{trajectory}$ will not give a constant anymore but will change over time. In this case the torque-angle relation will not be a straight line anymore. Moreover, at some instants $\frac{dT}{d\theta}$ will be infinite, meaning a stiff desired connection. This is of course impossible because the pressure inside the muscles is limited. Experiments showed that changing the stiffness during the trajectory costs a lot of energy and therefore a fixed stiffness strategy should be preferred. Reason is that each time the pressures inside both muscles has to raise to increase the stiffness, and the air has to be blow off to reduce the stiffness without delivering power at the joint. When for example the trajectory changes (due to new selected speed or step length), a new optimal stiffness has to be selected.

In the following experiments the trajectory for the hip, calculated by a trajectory generator, is imposed as trajectory on the pendulum. In order to generate this motion at higher speeds too, the mass at the end of the pendulum had to be reduced by 3.2kg. The new physical parameters are $\alpha = 0.66$, $m = 3.58kg$ and $I = 0.08kgm^2$. Figure 7 shows the computed torque-angle relation for different walking speeds. A remark that has to be made is that the trajectories are generated for walking, but the torques are only for swinging in the air for this specific pendulum. While the actual torques during walking will be different because walking consists of stance phases, double support phases, swing phases and impacts. The airmass consumption is measured for different walking speeds going from $\nu = 0.1m/s$ till $\nu = 0.6m/s$ in steps of 0.02m/s with a constant step length of $\lambda = 0.2m$. The stiffness range goes from 50Nm/rad till 150Nm/rad in steps of 5Nm/rad. A valley of minimal airmass consumption can be found which starts from a speed of 0.4m/s. The optimal measured stiffness values for the different walking speeds is plotted in figure 8. The minimal stiffness was 50Nm/rad, this explains the flat line between 0.1m/s and 0.4m/s. A first order linear regression has been performed on the torque-angle curve for each speed. An example is given in figure 7 and is shown by a dashed line. The slope of the linear regression line is a stiffness value which is plotted in figure 8. One can see that both curves have a similar course. At low walking speeds the motion is slower than the natural motion (average slope is positive) and using compliance is not possible. The strategy can neither be used when the slope is negative but is lower than the lowest possible stiffness, which is here 50Nm/rad.

![Fig. 7. Torque-angle relation for inverted pendulum hip trajectory with first order linear regression lines](image)

Figure 9 depicts the torque-angle relation of the hip joint for the real walking robot Lucy. When the average stiffness strategy of the torque-angle relation of the hip of the walking robot is calculated, a stiffness of 42Nm/rad is obtained. This is lower than the minimal attainable stiffness. In other words, the maximum walking speed of the robot is too slow to have the optimal stiffness lying in the feasible stiffness range. So, for now it is not sensible to implement this strategy in the real biped, due to its current walking speed limitation.

To conclude, this average stiffness strategy to calculate the optimal stiffness seems to be interesting to apply. An advantage of this strategy is that it is also applicable to other designs of passive compliant actuators.

VI. CONCLUSION

In this paper a strategy is proposed to combine active trajectory tracking for bipedal robots with exploiting the natural dynamics by simultaneously controlling the torque and stiffness of a compliant actuator. The goal of this research is to preserve the versatility of actively controlled humanoids, while
reducing their energy consumption. A compliance controller was proposed to find an optimal compliance dependent on the desired trajectory and physical properties of the system. The idea behind the mathematical formulation is to fit the controllable stiffness of the actuator to the natural stiffness of the desired trajectory. Because changing the stiffness over the trajectory is very energy-inefficient, an average stiffness strategy is proposed. The average stiffness is calculated by taking the slope of the the first order linear regression line of the torque-angle curve. The strategy is not implemented in the real biped Lucy. The current maximum walking speeds are too low to use the proposed average stiffness strategy for exploiting the natural dynamics.

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