Design and Control of a 3D Biped Robot Actuated by Antagonistic Pairs of Pneumatic Muscles

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***Abstract*— A joint driving mechanism with antagonistic pairs of muscles is supposed to be essential for humans and animals to realize various kinds of locomotion such as walking, running, and jumping. This paper describes design and control of a biped robot "Pneu–Man" whose joints are driven by antagonistic pairs of McKibben artificial muscles. Since the body is well-designed for walking, required control is surprisingly compact. The experimental results demonstrate the walking performance of Pneu–Man.**

***Index Terms*— biped walking, pneumatic actuators, passive dynamic walk, McKibben artificial muscles**

I. INTRODUCTION

A joint driving mechanism with antagonistic pairs of muscles is supposed to be essential for humans and animals to realize various kinds of locomotion such as walking, running, and jumping. When he/she relaxes the muscles, the joint becomes passive and he/she can move the body in a ballistic manner according to the body dynamics. He/she can change the joint compliance so as to adapt to the terrain by regulating the force exerted by the muscles. If the exerted force is large enough, the joint becomes stiff and is supposed to be position controlled.

There have been several researches on bipedal walking driven by such artificial antagonistic mechanisms [1], [2], [3], [4]. Verrelst et al. built a biped robot "Lucy" driven by Pleated Pneumatic Artificial Muscles [4]. However, the robot cannot really walk yet, but can swing its leg in the air. They controlled all the joints by a PI position controller, and did not take advantage of antagonistic drive such as changing the joint stiffness. As a result, they could not really utilize the dynamics of the robot.

On the other hand, Wisse and his research group developed a series of pneumatic actuated biped robots "Mike" [1], [2], "Max" [2], and "Denise" [2], [3] by adopting McKibben artificial muscles [5]. In spite of the complex characteristics of the artificial muscles such as time delay, hysteresis, and non-linearity, they effectively utilized the muscles to drive the walking robot, by making use of the well-designed dynamics for Passive Dynamic Walking [6]. Since they mainly focused on the energy consumption, they did not apply antagonistic drive for all joints, but only for the hip joint.

This paper describes design and control of a 3D biped robot "Pneu–Man" that has 10 joints driven by antagonistic pairs of McKibben actuators: 1–DOF arms and 4–DOF legs. Since every joint is controlled by a pair of artificial muscles, it has totally 20 muscles. To deal with the complicated dynamics of the actuator, we dedicated ourselves to design the robot very carefully. We adopt round soles that are advantageous for ballistic walking, and two arms connected with the opposite legs to keep the sideway balance. Some of the muscles are not controlled in real-time, but are pre-pressured so as to realize preflex [7], [8]. To apply pre-pressure, we adopt 3-position electrical valves. We propose a simple control scheme to realize walking of the robot making use of the well-designed dynamics.

This paper is organized as follows. Firstly, we describe the design of the biped robot "Pneu–Man". Secondly, we describe the control scheme for the robot utilizing the passive dynamics. Finally, we show several preliminary experimental results to demonstrate the performance of the walking robot.

II. DESIGN OF A 3D BIPED WALKER "PNEU–MAN"

If the body is well-designed, it reduces the control cost, not only amount but also quality. In this section, we introduce several design features of the biped robot Pneu–Man.

A. Mechanical design

In figure 1, we show photos of the biped robot. The sketch figure 2 shows its rough size and joints. It has an upper body, two 4-DOF legs, and two 1-DOF arms, totally 10-DOFs. The arm only has 1-DOF to lift sideways. The leg has a 1-DOF hip joint, a 1-DOF knee joint, and a 2-DOF ankle. The ankle has a ball joint and is driven by 2 pairs of artificial muscles along roll and pitch axes.

Its hight and weight are 0.83[m] and 7.0[kg], respectively, including a micro processor, 40 electrical valves, a battery for the processor and the valves, two CO_2 gas bottles to drive the artificial muscles(See weight of parts in the table I). The robot is basically self-contained.

We picked up several ideas out of passive dynamic walking [2]: round soles, the weight balance, and the arm movement. The curvature of the sole is 0.22[m], almost 1/3 of the leg length. The micro processor, the air valves, and their battery are on the body so as to make the gravity center as high as possible, which may increase the walking stability. Each arm is physically connected to the opposite leg, which may be effective to avoid a pivot turn around the supporting leg.

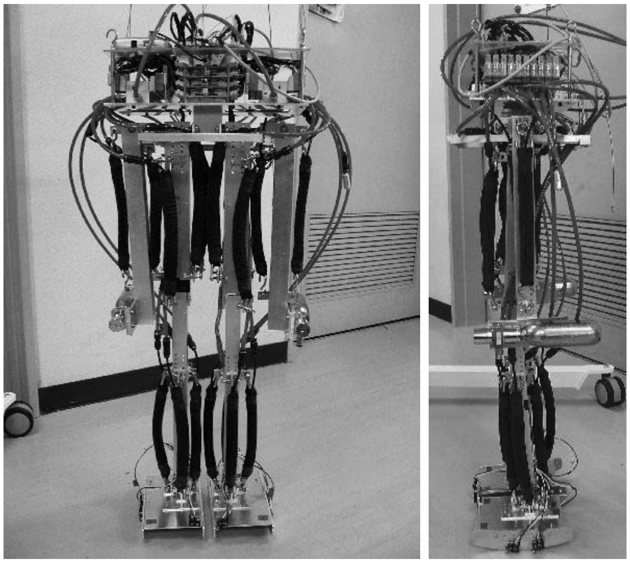

Fig. 1. A 3D pneumatic actuated walker "Pneu–Man". It has 10 joints with 10 pairs of McKibben artificial muscles, totally 20 muscles. CO_2 bottles are attached to tips of arms for balancing.

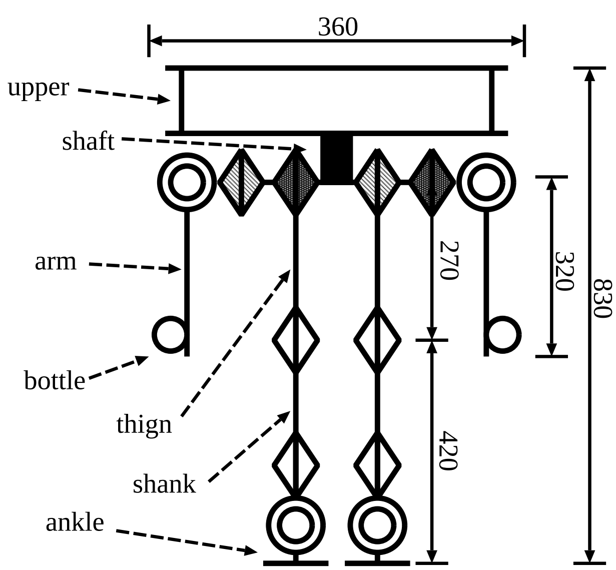

Fig. 2. A sketch of the 3D walker "Pneu–Man". The swing joint of left arm is physically connected to the right hip joint, and that of right arm to the left hip joint.

B. Air circuit design

Since the physical property of the robot body is well-designed, the required control for walking is simple and cheap. We could adopt electrical switching valves instead of popularly used proportional valves, which makes the weight and volume surprisingly less.

The switching valves is not suitable for precise control, and moreover, the air muscle has a large time delay and hysteresis, it is relatively difficult to control its force in an on-line manner. On the other hand, if the muscles are properly pre-pressured, their elasticity and damping can be utilized for free without time-delay. These zero-delay response is called *preflex* and is supposed to play a great role for stabilizing the walking, running, and jumping [7], [8].

TABLE I
LIST OF WEIGHT OF EACH PART

	Weight[kg]
Arm.assy	0.24×2=0.48[kg]
Thigh.assy	0.24×2=0.48[kg]
Shank.assy	0.22×2=0.44[kg]
Ankle.assy	0.20×2=0.40[kg]
Bottle	0.60×2=1.20[kg]
Shapt.assy	0.25[kg]
upper body	2.5[kg] (valve 0.08×20=1.60[kg] + manifold + aluminium parts)
other parts	approx. 1.25[kg]
Total	approx. 7.0[kg]

Fig. 3. McKibben artificial muscles by Hitachi Medical Corporation. When it contracts, its diameter becomes 20 [mm]. It generates 800 [N] when it is supplied with 0.7 [MPa] pressure.

The minimum requirement for the valves to control a well-designed biped walker is 2–position: open to the supply or open to the atmosphere [1]. However, since we intend to utilize preflex to realize various types of locomotion by this robot, we carefully selected off-the-shelf 3–position valves (open to the supply, close, and open to the atmosphere).

We used McKibben artificial muscles produced by Hitachi Medical Corporation shown in figure 3. When it contracts, its diameter becomes 20 [mm]. It generates 800 [N] when it is supplied with 0.7 [MPa] pressure.

C. Electrical design

Since we do not control the joint positions precisely but only control time to open and to close the valves according to the touch sensor information, we did not need many sensors such as joint angle sensors and pressure sensors. As a result, not only we could reduce the total weight of the robot, but could reduce the required specifications for the processor since required amount of calculation and numbers of I/O ports and of other interfaces decrease. We only need 40 binary outputs for controlling all the muscles and 2 binary input for the touch information, at least.

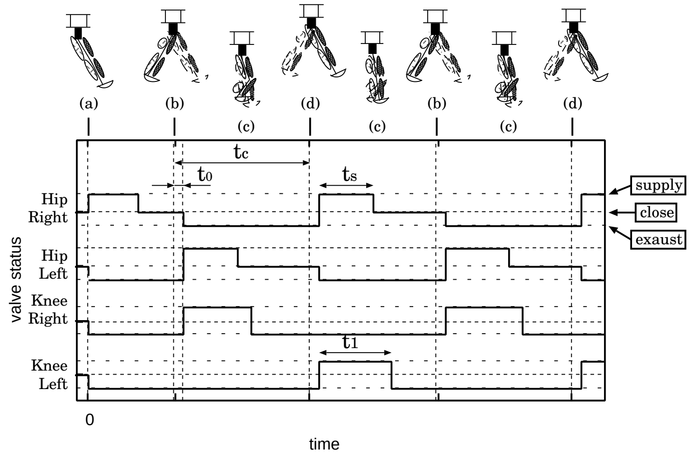

Fig. 4. The control scheme for supplying/exhausting/closing the valves

Since required control for realizing walking of the robot is so small and cheap, we could adopt a small RISC processor H8/3069 (24MHz). The energy consumption of the board and switching valves are so small that we could use a small Lithium ion battery for them.

III. Walking control of the biped “Pneu–Man”

We apply ballistic control that opens the valves for swinging the free leg fixed time after foot impact, which is almost the same law proposed in [1], [2], [9] for 2D walkers. The only sensors that the robot has are several touch sensors on the soles.

In figure 4, we show the operation strategy of the valves. In the figure, the operation of back muscles of the hip joint and of knee joints are indicated. The rest, the fore muscles of the hip joint, the fore muscles of the knee joints, and the muscles of the ankle joints are pre-pressured before we start the walking experiments. Since we cannot precisely control the amount of air, we instead determine the open duration to the supply air 0.7 [MPa]. That of fore hip muscles, of fore knee muscles, of fore pitch ankle muscle, of back pitch ankle muscle, of outer roll ankle muscle, and of inner roll ankle muscle are 200 [ms], 200 [ms], 270 [ms], 80 [ms], 500 [ms], and 170 [ms], respectively. These values are determined through experiments in a trial and error manner.

The control parameters we can change are t_0 and t_s, time to start swing after the free leg touches the ground and valve opening duration to swing the free leg, respectively. t_c is walking cycle, which is the consequence of the control. We also can change t_1, the valve opening duration to bend the knee, which is, however, not effective to change the overall behavior of the robot.

IV. Preliminary walking experiment

We conducted several experiments on the robot. Firstly, we search for the sufficient control parameter that makes the robot walk. Secondly, we investigate the relation between swing and walking cycle. Thirdly, we investigate the effect of stiffness of the ankle joints.

Fig. 5. A walking sequence of the developed biped with proposed control

A. Realization of walking

We conducted experiments to demonstrate the walking performance of the system. We searched for the best walking parameters for stable walking by trial and error. When $t_0 = 10$[ms] and $t_s = 250$[ms], the robot could walk more than 16 steps. In the experiment, due to the experimental cost reason, we did not use the CO_2 bottles but the air compressor connected with tubes, which limits the movement of the robot, unfortunately. In figure 5, we show a walking sequence of the developed biped with the proposed controller.

B. Relation between walking cycle/steps and swing duration

We investigated relation between valve opening duration for swinging the free leg t_s and the walking cycle t_c (figure 6) and that between t_s and average walking steps (figure 7). For each control parameter, we conducted 30 walking trials. We can find positive correlation between the walking cycle and the duration. This relation can be utilized for controlling the walking cycle by changing swing duration [9].

From figure 7, we could not find any remarkable relation between the swing duration and the walking steps. The reason may be that the walking is strongly affected by the initial condition of the robot. Since a human operator *through* the robot in every trial, we could not control the initial conditions precisely. We tried to get rid of the effect by conducting 30 walking trials for each control parameter and taking the average, but still we have a large variance in the performance which we can find in the figure 7. We should study in more detail about this point.

C. Relation between walking cycle/steps and ankle roll stiffness

We investigated relation between the duration to supply air to the outer muscles of ankle roll joints t_{ar} and the walking cycle t_c (figure 8). The relation between t_{ar} and walking steps is also investigated and the result is shown in figure 9. For each control parameter, we again conducted 30 walking trials. We can find that the ankle joint stiffness along roll axis does not affect to the walking cycle very much.

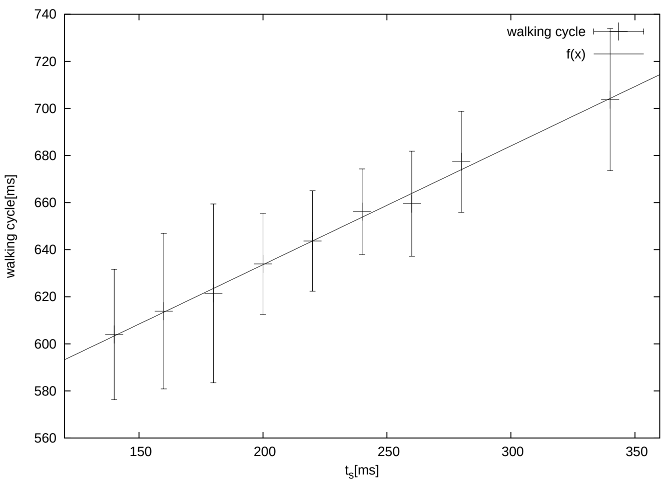

Fig. 6. Relation between the swing duration t_s and the walking cycle t_c. We can find positive correlation between the walking cycle and the swing duration.

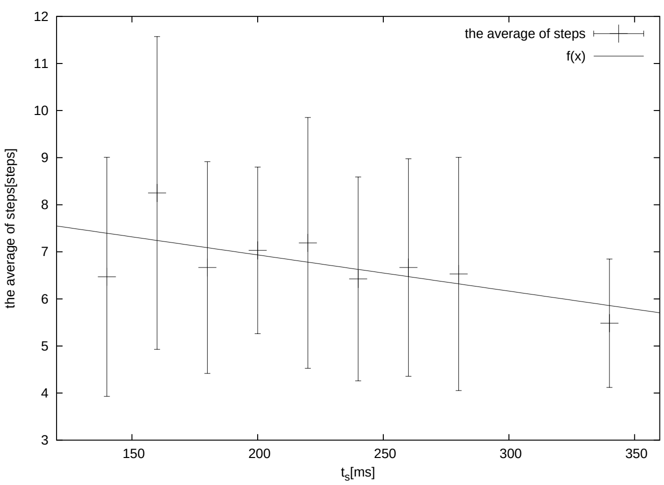

Fig. 7. Relation between the swing duration t_s and the average walking steps. It is difficult to find relation since the variance is quite large.

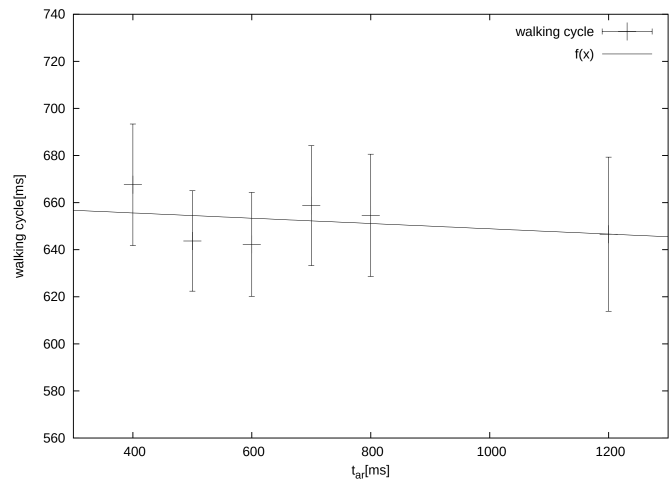

Fig. 8. Relation between the duration to supply air to the outer muscles of ankle roll joints t_{ar} and the walking cycle t_c. The change of the ankle joint stiffness along the roll axis does not affect the walking cycle very much.

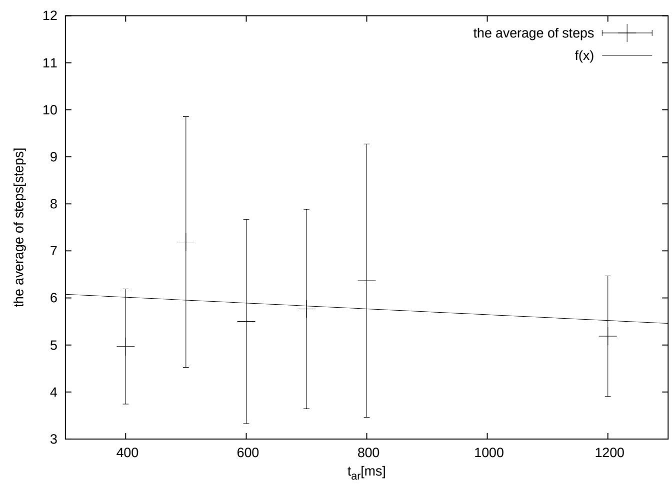

Fig. 9. Relation between the duration to supply air to the outer muscle of ankle roll joint t_{ar} and the walking steps. It is difficult to find relation since the variance is quite large.

From figure 9, we again could not find any remarkable relation between the roll ankle joint stiffness and the walking steps.

D. Relation between walking cycle/steps and ankle pitch stiffness

Finally, we investigated relation between the duration to supply air to the fore muscles of ankle pitch joints t_{ap} and the walking cycle t_c (figure 10). The relation between t_{ap} and walking steps is also investigated and the result is shown in figure 9. We can find that the ankle joint stiffness along pitch axis also does not affect to the walking cycle very much.

From figure 11, we again could not find any remarkable relation between the pitch ankle joint stiffness and the walking steps.

E. Summary of preliminary experiments

Although the initial condition for walking cannot be precisely controlled, the result we have got shows several evidences. (1) There is positive correlation between the walking cycle and the valve opening duration for swinging the free leg, which can be utilized for controlling the walking cycle. (2) The stiffness of the ankle joint does not affect the walking cycle so much within the range we have tested. However, we should study further about it since the tested range of parameter is limited. (3) Number of walking steps is strongly affected by the initial conditions.

V. Conclusion and Discussion

This paper describes design and control of a 3D biped robot “Pneu–Man” that has 10 joints driven by antagonistic pairs of McKibben actuators. We introduced the design concepts, and described technical details. We conducted several preliminary experiments and demonstrated that the walking robot can walk on a flat plane stably.

In the preliminary experiments, we investigated the effect of stiffness of the ankle joints, and found that it does not affect

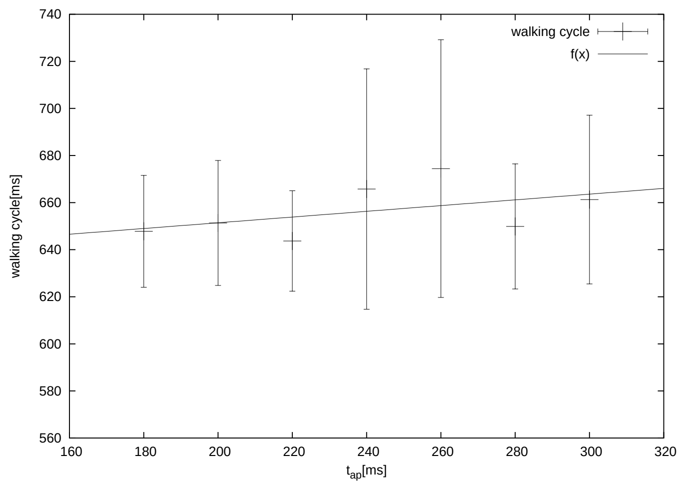

Fig. 10. Relation between the duration to supply air to the fore muscle of ankle pitch joint t_{ap} and the walking cycle t_c. The change of the ankle joint stiffness along the pitch axis also does not affect the walking cycle very much.

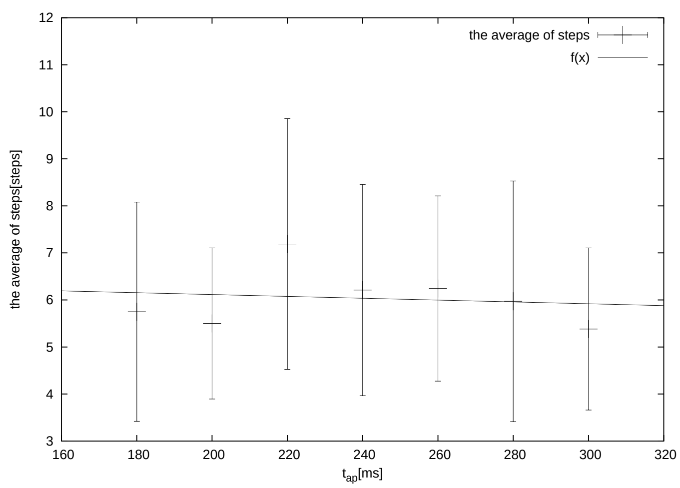

Fig. 11. Relation between the duration to supply air to the fore muscle of ankle pitch joint t_{ap} and the walking steps. It is difficult to find relation since the variance is quite large.

to the walking cycle so much within the range of the control parameter we took. On the other hand, when a robot runs, such *preflex* is supposed to play a great role [8]. We should further study the effect of ankle stiffness more precisely.

The most formidable issue of such biped robot based on passive dynamic walk is "initial condition". As we have already discussed, the variance of the initial condition is quite large in these experiments since a human operator launch the robot to walk. To eliminate the effect of such variance as much as possible, we conducted many walking trials, but we still have it. We should take such effect into account, and continue to study on the stability of the robot.

The control parameters are basically tuned by the human operator. We should study whether learning schemes are effective or not to acquire stable walking. Since the dynamics of the robot is well-designed, we speculate that the learning seems to be easier than without designing *good* physical properties [10].

ACKNOWLEDGEMENT

The authors would like to thank Prof. Minoru Asada and Dr. Masaki Ogino for their variable comments and discussions on this research. This research was partially supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Exploratory Research #16650037 (2004), and Grant-in-Aid for Scientific Research (A) (2005).

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