Design and Control of 2D Biped that can Walk and Run with Pneumatic Artificial Muscles

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Abstract—We humans utilize body compliance provided by antagonistic muscles to realize dynamic locomotion such as walking, jumping, and running. In this paper, we introduce design of a biped robot driven by antagonistic pairs of artificial pneumatic muscles so that it can change joint compliance according to the desired dynamic locomotion. We then propose simple controllers for realizing walking, jumping, and running. Experimental results demonstrate that the robot can dynamically walk, jump, and run by the proposed controllers.

I. INTRODUCTION

Biped locomotion is one of central problems of robotics which has been tackled by many researchers. So far, they have succeeded to realize static and dynamic walking, jumping, and running. However, most of existing biped robots can realize only one locomotion mode and very few can locomote in two or more modes.

Focusing on running and jumping, Raibert carried on pioneering research on biped running and developed a biped robot which could run and jump (somersaults) [1]. Since then, many researches followed the way to adopt serial springs to preserve and release energy for running. However, constant elasticity of the leg will prevent the robot from being adaptive to the locomotion mode and change of terrain.

Attempts to realize running by ordinary humanoids are made as well. Kajita et al. developed a humanoid biped HRP-2LR which could walk and run [2]. Honda Motor Co., Ltd. developed a humanoid ASIMO and realized stable walking and running [3]. These humanoids are equipped with electric motors geared with high reduction ratio so that they can supply enough torque to drive the joints. Therefore, the joints do not have back-drivability against the external force and torque. They solved the problem basically by designing the trajectory of joints and elaborate force feedback.

On the other hand, we humans utilize body compliance provided by antagonistic muscles to realize dynamic locomotion such as walking, jumping, and running. Elasticity of antagonistically driven joints can be easily changed by tuning the tension of the muscles. If the robot is equipped with such muscles, they can be utilized to change the compliance of the robot, and as a result, it can realize smooth and stable walking and running by changing the compliance. Such compliance provided by the muscles can be utilized for free for stabilizing dynamic locomotion without time-delay [4], [5] whereas the compliance provided by force control naturally has large time delay.

Following this idea, we designed a biped robot driven by antagonistic pairs of artificial pneumatic muscles so that it can change joint compliance according to the desired locomotion. Caldwell et al. [6] and Verrelst et al. [7] also made pneumatic-driven bipeds, but they only realized one locomotion modality, that is, walking. In this paper, we introduce the design of the robot and propose simple controllers for achieving dynamic locomotion.

The rest of the paper is organized as follows. First, we introduce the design of the biped driven by artificial pneumatic muscles. We then propose simple controllers for realizing walking, jumping, and running. Finally, experimental results demonstrate that the robot can dynamically walk, jump, and run by the proposed controllers.

II. 2D BIPED ROBOT DRIVEN BY PNEUMATIC ARTIFICIAL MUSCLES

A. Mechanical design for walking, jumping and running

The aim of this paper is to develop a biped robot that can not only walk but jump and run. Design principles for such a biped should be different from the one only for single locomotion mode.

If the biped is designed base on the idea of Passive Dynamic Walking [8], it uses knees only to clear the ground and does not need any ankle. The knee is stretched and rigid when the foot hits the ground. The conventional walking humanoids are driven by electrical motors via gears, and their knees are controlled rigidly so as to track the pre-determined trajectories, e.g. [9]. On the other hand, the robots specially designed for running normally have serial elasticity in their legs [1]. A humanoid robot can also emulate such serial elasticity by bending knees and setting compliance, which requires high bandwidth feedback for generating reaction force according to force sensor measurement [2]. In short, knees should be rigid for walking, and should be compliant for jumping and running.

On these contradictory conditions, we design the biped robot so that it can change the joint compliance based on the locomotion mode. We adopt antagonistic joint drive mechanism with two elastic artificial muscles. In Fig. 1, we depict the mechanical design of our 2D biped robot: it has one hip joint, two knee joints, and two ankle joints. To realize walking based
Fig. 1. Mechanical design of the 2D biped robot that can walk, jump, and run: it has 1 hip joint, 2 knee joints, and 2 ankle joints. All the joints are antagonistically driven by elastic artificial muscles.

on passive dynamics, the robot does not need ankles [10]. The robot does not need any ankle for running as well if the mass of the legs can be neglected with respect to the body mass [1]. However, the developed robot consists of two legs without the torso, so it needs ankles to change the hopping direction.

B. Muscle and air design

We adopt McKibben type pneumatic actuators [11] to drive the joints since they are elastic and supposed to be advantageous for preserving energy. However, the actuators have large hysteresis and are highly non-linear. They are not suitable for trajectory tracking control. We resolve such a difficulty of the actuators by designing the dynamics of the robot properly following the idea of the previous work [10], [12]. The actuators are basically controlled in a feedforward manner according to the fixed sequence of the valve operation. We adopt 5-port solenoid ON/OFF valves with closed center position so that we can fix the compliance by closing it. In Fig. 2, we show the air circuit to control an artificial muscle.

C. Control architecture design

Since we adopt solenoid valves, the controller becomes extremely simple: it needs two bits (on or off of supply/expel valves) to control a muscle. The biped has three legs to restrict its motion in the sagittal plane, therefore, it has totally 18 muscles: 4 for each ankle, 4 for each knee, and 2 for the hip, that is, 36 bit ports are enough for controlling the whole robot.

To sense the state of the robot, we adopt touch switches on the soles [10], [12], but did not install any other sensors such as a gyro or accelerometer. The switch is installed on the heel of each leg. The whole control architecture is shown in Fig. 3.

III. CONTROLLERS FOR DYNAMIC LOCOMOTION

A. Dynamic property of the artificial muscle

There is time delay between the inner pressure of the muscle and operation of the valve (Fig. 4). We conducted preliminary experiment to supply and expel 0.6[MPa] air to an unloaded McKibben artificial muscle whose length is 0.15[m]. We found that the time delay is more than 0.4[s], which is quite large. We also conducted experiments on different pressure and on different length of the tube, but the delay was almost the same. Therefore, we can infer that the delay comes from the limit of flow of the air valve. However, the delay is not a defect, but we can utilize such delay for changing the compliance of the muscle by regulating the opening duration of the supply and expel valves.
Fig. 4. There is time delay between the inner pressure of the muscle and operation of the valve. In this preliminary experiment, the muscle is unloaded. The supply valve is open at 1[s], and expel valve is open at 3[s]. We can see more than 0.4[s] delays.

B. Valve operation for dynamic walking

We propose a valve operation for dynamic walking (Fig. 5), which is almost the same one proposed in [12] except ankle valve operation. The knee and ankle extensor muscles are filled with certain amount of air at the beginning of the walking trial, and are not operated but “closed” during the experiment. The muscles of the stance leg are not operated as well. The valve operation is initiated by the touch signal provided by the sensor embedded on the heel. After the signal, the ankle flexor is activated and fixed for $T_s$ to kick off the ground. To get the propulsion force, the hip extensor is activated for $T_w$ while the flexor lost the air. After $(T_w + T_1)$[s], the robot expel the air from the knee flexor so that the swing leg clear the ground.

Pulse wave modulation (PWM) is commonly used to control the pneumatic actuators when they have on/off alternate valves. If we use the technique, we can control the motion of the leg precisely. However, on the other hand, we have to design its “desired trajectory”, which is another big problem. In this paper, we simply let the robot move in a ballistic manner so that we can avoid to design the trajectory explicitly.

C. Valve operation for running

Valve operation for running is more complicated than that for walking (Figure 6). The operation of the hip is the same as that of walking. After the touch, the robot closes all valves of stance leg so that it has certain compliance against the touch down force. After $T_{ts}$, the knee extensor muscle is supplied while the flexor is expelled so that the stance leg becomes stiff. At $(T_{ts} + T_{i1})$, the ankle extensor is supplied to kick the ground. At $(T_{ts} + T_{ww})$, all the valves of the leg are closed when the robot is supposed to be in the air. Then, after $T_{t2}$, the knee bends so that the leg can be the swing leg and clear the ground. The ankle is also flexed so as to clear the ground.

After the leg becomes a swing one, it continue the same operation until $T_{wws}$. Then, all the valves are closed. After $(T_{wws} + T w 1)$, the knee is extended to be ready for the next impact. The flexor is expelled so that the tension of the knee becomes smaller.

IV. WALKING, JUMPING, AND RUNNING EXPERIMENTS

A. A prototype for multi-modal locomotion

We have developed a prototype 2D biped robot shown in Figure 7. The height, width, and weight of the walker are 0.90[m], 0.26[m], and 6.0[kg], respectively. It has four legs to avoid sideways swinging, two of which are connected to each other. The outer legs are connected with each other by a boom.

The robot is self-contained that has 2 air bottles with regulators, all control valves, a micro computer board, and an electrical battery. It has 14 sets of 3-position solenoid valves...
produced by SMC Corp. that weight 0.84[kg]. It has it ON/OFF switches that detect collision with the ground.

All the joints are driven by McKibben pneumatic actuators by HITACHI Medical Corporation (Figure 8). The length and radius of the actuator are 0.2[m] and 0.020[m] (when it contracts), respectively. It generates approximately 800[N] when the pressure in the inner tube is 0.7[MPa].

The robot has 5 degrees of freedom: 1 hip, 2 knees, and 2 ankles. Each of the hip and 2 knees is driven by a pairs of muscles. To symmetrize the robot, the ankle of the inner leg are driven by four pairs of muscles while each ankle of outer legs is driven a pair of muscles. Totally, the robot has 14 muscles.

The robot has a touch sensor on each foot. The on/off information is fed to a single chip micro computer H8 (Renesas Technology Co.). According to this information, the computer outputs the open/close commands to the solenoid valves. It has two CO$_2$ bottles whose pressure is 1.2[MPa] as air sources each of which weighs 0.7[kg] and a battery that weighs 0.1[kg].

In the following experiments, the pressure of the air source was 0.6 [MPa]. Although walking can be realize with lower pressure, we tried to investigate walking, jumping, and running in the same pressure.

B. Walking Experiment

Firstly, we demonstrated that the robot can walk on a flat plane. In Figure 9 we show a sequence of walking. The pressure of the air source was 0.6 [MPa], which is the same pressure used for jumping and running. Since walking is less dynamic behavior, less pressure e. g. 0.4 [MPa] or less, could make the robot walk stably. The walking parameters $T_s$, $T_w$, and $T_b$ are 80[ms], 100[ms], and 250 [ms], respectively. The average walking cycle, the average stride, and the average velocity was 1.38[s], 0.35[m], and 0.51[m/s], respectively. The robot could actually walk stably that we could change the walking parameters within a certain range.

C. Jumping Experiment

Before we let the robot run, we confirmed its ability for dynamic locomotion by letting it jump. Its jumping is shown in Figure 10.

Hip muscles, knee flexors and ankle extensors are filled with certain amount of air at the beginning of the jumping trial, and are not operated but closed during the trial. After sensing a touch signal, the knee extensors and the ankle flexors are supplied with the air so that the robot jumps up.

The flight time and height were 270[ms] and 120[mm], respectively. The robot could jump several times, up to 7. Since the robot was not equipped with attitude sensors such as gyro sensors, stability of jumping is not really ensured. However, we could confirm the robot’s ability for dynamic locomotion.

D. Running Experiment

Time parameters used for the experiment are determined by trial and error. They are shown in Table I. The speed of running was 1.13 [m/s]. The robot could only realize 7 steps of running in this experiment. It could not keep the stable running because of not having feedback from external sensors. I suppose that we could apply a feedback control proposed in [1] if we equip the sensor that can observe the attack angle of the robot.

| $T_{hs}$ | 130 | $T_{hw}$ | 150 |
| $T_{1s}$ | 130 | $T_{tw}$ | 150 |
| $T_{11}$ | 50 | $T_{21}$ | 50 |
| $T_{w1}$ | 140 | $T_{w1}$ | 100 |
| $T_{w2}$ | 150 | $T_{w3}$ | 30 |

V. Summary and Future work

Based on the idea that the compliance of the robot should be changed for different locomotion modes, we have designed
the biped robot so that it can change the joint compliance based on the locomotion mode. We have adopted antagonistic joint drive mechanism with two elastic artificial muscles. We have proposed simple controllers for realizing walking, jumping, and running. These behaviors have been experimentally demonstrated by the prototype biped robot.

As already discussed, the robot does not have any feedback from the attitude sensors. It will surely increase the stability. However, time delay and hysteresis of the actuator are not trivial for applying feedback control base on the sensory information. There should be several problems to be solved for more stability. One of the promising way is to apply step-by-step feedback based on the previous attack angle [1].

Now, for simplicity, the robot has 4 legs to avoid falling down sideways. We are investigating on two-leg biped for the same target, but in this case, it is crucial to apply additional balance control for lateral motion.

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Fig. 9. Walking experiment: the average walking cycle, the average stride, and the average velocity was 1.38[s], 0.35[m], and 0.51[m/s], respectively. Air pressure was 0.6[MPa]. The robot could walk more than 30 steps.

Fig. 10. Jumping experiment: the flight time and height were 270[ms] and 120[mm], respectively. Air pressure was 0.6[MPa]. The robot could jump several times.

Fig. 11. Running experiment: the flight time and speed were 0.12[s] and 1.13[m/s], respectively. Air pressure was 0.6[MPa]. It could run 5 steps at most.