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Active and Passive Compliance Mechanisms in Legged Robot Locomotion

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Abstract – Legged robot locomotion is a challenging field. Problems can occur during locomotion such as morphology, controller, and ambience factor, to name a few. However, there are always trade-offs in designing legged robots, for example, speed against stability, number of limbs against complexity of controller, and mass of the robot against energy consumption of the actuators. Therefore, the problems can be minimized when the hardware and software complement each other. Active compliance mechanism describes a closed-loop system which actively sense-and-act according to the surroundings. Passive compliance mechanism, as its name suggests, is a regulatory mechanism in which it does not rely on the controller to actively respond in order to achieve adaptability. The composition materials of a legged robot provide the advantages during locomotion. In this review, we are going to investigate the differences of the mechanisms and how they can be complemented to diminish problems during locomotion.

Keywords: Active compliance mechanism, legged robot, locomotion, passive compliance mechanism

Introduction

Legged robots belong to the family of mobile robots. Mobile robots are capable of moving around an environment by means of discrete foothold, continuous foothold, or hybrid foothold. A legged robot possesses a number of feet, which provide the maximum number of supporting points. As opposed to a legged robot, a wheeled robot locomotes around the environment with a continuous foothold. A hybrid mode combines the advantages of both legged and wheeled robots by producing continuous support on flat terrain and discrete support on uneven terrain. Mobile robots can be manually controlled or operate autonomously.

Walking is a sequential mass shifting procedure which comprises a series of actuation of joints in a systematic manner. Several popular methods to generate a walking motion are zero-moment point (ZMP) (Vukobratović & Borovac, 2004), inverted pendulum (Kajita et al., 2002), inverse dynamics (Fujimoto & Atsuo, 1998), central pattern generator (Ijspeert, 2008), tri-pod gait (Cham, Karpick, & Cutkosky, 2004), to name a few. Therefore, it is a strenuous effort to perform the walking task.

The interaction between a legged robot and the arbitrary surroundings is challenging because of high uncertainties ahead. Therefore, designing an intelligent controller is the ultimate goal of a legged robot locomotion. Floating-base inverse dynamics on LittleDog exhibits superior walking performance on uneven terrain by a precise foothold selection and a variable step length (Buchli, Kalakrishnan, Mistry, Pastor, & Schaal, 2009). However, a frequent controller activity results in high energy consumption and relatively low walking speed. Moreover, crashing with the surroundings and excessive foot impact forces are less desirable.

In this study, we are going to review two main streams of solving legged robot locomotion problems, namely, active compliance and passive compliance mechanisms. Active compliance mechanism is a closed-loop system, which the robot responds to the environment according to the sensory information. In contrast, passive compliance is an open-loop system, which the robot responds to the environment based on the body regulatory mechanisms, such as spring-damper mechanism, adjustable joint, and link stiffness.

In the next section, active compliance and passive compliance mechanisms are equally investigated. The investigation includes fundamental principles of both mechanisms. Then, the importance of fusion of active and passive compliance mechanisms is discussed. In the conclusion section, problems of designing legged robots are summarised.

Active compliance mechanisms

As its name suggested, active compliance mechanisms require sensory information to aid decision making. The behaviour of the robot is solely reflected from sensory information. Therefore, an intelligent control paradigm is required in order to produce a walking behaviour.

A legged robot possesses sensors, which are attached around its body to perceive the world. Robot cognition is a house of storing and retrieving information to aid a decision-making process. Kaplan (2000) implemented a learning mechanism in which the robot is able to interact with its user in order to acquire knowledge (object recognition). A cognition process is important because it allows the robot to understand the world, and acts accordingly. Figure 1 exemplifies three different layers of constructing a controller for a legged robot locomotion. The highest level is the main command to the robot, i.e. wandering aimlessly or target-oriented locomotion. Then, based on the start-point and the end-point, the path is planned. Lastly, according to the prearranged path, the trajectories of the joints are mapped.

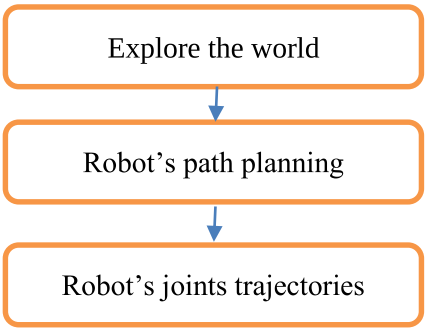

Figure 1: Hierarchical classification of active compliance mechanism controller

The controller can be designed to act reactively or deliberatively. A reactive controller is defined as an action that is caused directly by the controller. A remarkable example is from Kimura, Fukuaka, and Cohen (2007) in which the robot is programmed with CPG to produce walking behaviour; reflexes and responses are designed to provide immediate response in order to cope with uncertainties (Kimura, Fukuoka, & Cohen, 2007). On the other hand, a deliberative controller is meant for prudent jobs. Tasks such as mine removal cannot afford a single failure, even for a minor case (Kato & Hirose, 2001). Brooks asserted that the traditional AI is weak to problem solving, because it requires internal representation of the world to make every decision. Comparatively, he proposed Subsumption Architecture (SA) of which a hierarchical set of layers is used to represent the behaviours (Brooks, 1991). Next, the robot behaviour is elicited by the mutual inhibition of signals from different layers. Details of traditional AI and SA are illustrated in Figure 2.

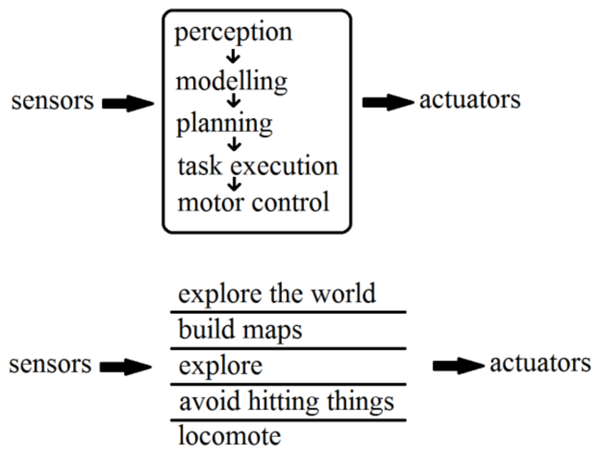

Figure 2: The principle of traditional AI is explained. The sensory information is required to penetrate into every single layer before a decision can be made. Therefore, it is time consuming and not applicable to highly dynamic world. Conversely, SA as shown in the lower figure decomposes the behaviour into layers with various priorities (Brooks, 1991)

Passive compliance mechanisms

A passive compliance mechanism, on the other hand, is a regulatory mechanism that does not rely on the controller to actively respond in order to achieve adaptability. The composition materials of a legged robot provide the advantages during locomotion. As observed in nature, we experience the flexibility and durability of bone structure, which allows us to perform prominently in sports, recover from stumbling, and protect the viscera against forces. Several studies have been conducted on tensile characteristics of human rib cortical bone, adaptability of bone properties to individual's physical activities, and biomechanical properties of bone (Natali & Meroi, 1989; Rittweger et al., 2000; Subit, de Dios, Valazquez-Ameijide, Arreigui-Dalmases, & Crandall, 2011).

There are a number of researches based on improving the material characteristics of the robot. For example, spring-damper mechanism (Poulakakis, Smith, & Buehler, 2005), variable link stiffness (Brown & Zeglin, 1998; Bailey, Cham, Cutkosky, & Full, 2000; Takuma, Ikeda, & Masuda, 2010; Galloway, Clark, Yim, & Koditschek, 2011), and adjustable joint stiffness (Pratt, Williamson, 1995; Poulakakis, Smith, & Buehler, 2005; Ham, Sugai, Vanderborght, Hollander, & Lefeber, 2009; Scarfogliero, Stefanini, & Dario, 2009). An experiment done on Scout II (Poulakakis, Smith, & Buehler, 2005) demonstrated the flexibility of the hip joints facilitate the running gait of the robot with only one actuator in a leg. The elasticity and flexibility of the materials bestow the capabilities of the legged robot to confront with various kinds of danger. Nonetheless, passive compliance mechanisms are still lack of flexibility, because the material properties are not changeable. Unlike living organisms, robots cannot adapt to the environment psychologically and physiologically.

Energy storage in links and joints are useful to eliminate transient effects of external perturbation on the robot (Kim, Clark, & Cutkosky, 2006). Because the limbs and torso are interacting in unison, the chain reaction of the extrinsic disturbances are not negligible. The effect is more distinguishable when a higher locomotion speed and bouncing gait are required (Poulakakis et al., 2005). The former indicates the continuous impact between the limbs and terrain results in instability of robot; the latter illustrates the importance of releasing and storing energies to realize the bouncy movement. Thus, passive compliance mechanisms deliver the supplementary function to combat against disturbance from surroundings and to enhance the mobility of the robot.

Discussion
In the previous section, we have revealed the functions of active compliance and passive compliance mechanisms. Next, we are going to make a comparative study on robot locomotion and animal locomotion, especially human. The study is divided into three facets, namely, pure active compliance mechanism, pure passive compliance mechanism, and combination of active compliance and passive compliance mechanisms.

Pure active compliance mechanism
Deliberative actions such as path planning, footstep placement on unstructured terrain require massive amount of signal processing. It emphasizes continuous perception-action cycle to generate the right behaviour to deal with current situations. The array of sensory information is utilized to determine the action which is more rewarding.

There is a number of researches to show that emotion affects decision-making in human beings. (Carver, Sutton, Scheier, 2000; Wood, Quinn, & Kashy, 2002; Baumeister, DeWall, Vohs, & Alquist, 2010) The effect is twofold: emotion causes behaviour (Baumeister, Vohs, DeWall, & Zhang, 2007), and behaviour pursues emotion (Baumeister, Stillwell, & Heatherton, 1994). The former explains that an action of an individual is caused by the inner state (such as joy, grief, angry, and thirst), e.g. he is giving up because the weather is bad. By contrast, the latter denotes an action taken to acquire or refrain from the inner state, e.g. he is striving to reach the destination because he triumphs for achievement. It is still difficult to implement an emotional decision-making algorithm on a mobile robot because of our limited understanding of the brain.

The concept of adaptive control is to control the movements of the joints in order to provide adequate joint stiffness and proper posture. Gait adaptation can be done by visual input, proprioceptive responses, force feedback at the feet, to name a few (Weingarten, Lopes, Buehler, Groff, & Koditschek, 2004; Manjanna & Dudek, 2015). A muscle-like property in the actuator can be realized by adjusting the parameters of the controller, and the joint position and stiffness can be varied according to various situations. A PD-controller is used to model a virtual spring-damper mechanism with the aim of increasing stability (Kimura et al., 2007). Xiong, Worgotter, and Manoonpong (2015) have created a modular neural network (MNN) controller to automatically tune the leg stiffness, thereby gaining adaptability on different surfaces.

Pure passive compliance mechanism
When the controller is inactive, a passive compliance mechanism demonstrates the practicality in a legged robot. A passive walker exemplifies the utilization of gravitational force to walk on slightly down slope without actuation (McGeer, 1990). The potential energy to kinetic energy conversion eliminates the power consumption from actuation. Besides, there is a 20% failure rate for a two- legged robot to walk steadily, mostly due to inappropriate initial conditions (Collins, Wisse, & Ruina, 2001).

A morphological design of the robot is an important factor for maximum locomotion efficiency. Centre of gravity, number of limbs, type of limbs, type of actuators, material, and size are important components to robot building. For example, the bow leg design by Brown (1998) shows the possibility of using a string to control the elastic leg for robot locomotion. The leg compressed and extended during landing and lifting. As a result, it eliminates the knee and ankle actuators to produce locomotion. Another example of a single rotary actuator to produce forward locomotion is EduBot by Galloway (2011). In order to increase the passive compliance of the robot on various terrain conditions, the stiffness of the leg is tuneable. The study also discusses the effect of leg stiffness on walking speed and terrain conditions.

In Takuma's (2010) work, a wire is holding a series of elastic discs and a rigid block, and is attached to a winch. The winch is used to control the flexibility of the spine. As a result, this structure produces a unique oscillation according to the degree of viscoelasticity. A simulation study is conducted to illustrate the effect of rigid spine, unidirectional flexibility spine, and bidirectional flexibility spine on passive running down on a slope (Kani, Derafshian, Bidgoly, & Ahmadabadi, 2011). The result shows that the bidirectional flexibility spine is the best in terms of stability and velocity. It is also worth mentioning that the joints are not controlled by actuators. Thus, the motion is generated by gravitational force. There are also many studies working on passive walkers. Thus, an energy efficient walker can be created using the concept of passive walkers with little power actuators to walk on slopes and flat terrains. In the next section, the combination of active and passive walking mechanisms is discussed in detail.

Combination of active compliance and passive compliance

Active compliance and passive compliance mechanisms are equally important for legged robot locomotion. It is recognizable in a complex situation, for instance, walking over uneven terrain, deformable surface, dynamic obstacles, and high speed locomotion. Because energy storage in the links and joints depress the external forces and disturbance, it indirectly regulates the behaviour of the robot. For example, a robot walks on a flat terrain with a fixed behaviour, and it stumbles over the uneven platform. The passive compliance mechanism is activated to buffer the ground perturbation.

Another example illustrating the importance of combination of active and passive compliance mechanisms is leg configuration in Figure 3. Usually, a robot with an insect leg configuration has its legs widely spread and has lower centre of gravity. On the other hand, a mammal leg configuration has a smaller support polygon and a taller centre of gravity. In this example, it shows that different leg configurations attribute to different stabilities, walking speeds, energy expenditures, etc. It would be a long explanation for detailed elaboration for leg configuration alone. Böttcher (2006) explains the energy expenditure, stability, leg configuration and number of legs in order to get the right combination in legged robot design. On the other hand, Jones and Hurst (2012) analyse the effect of leg configuration on running and walking legged robots. In the study of De Santos, Estremera, and Garcia (2005), the energy requirement of the actuators is reduced by strategically placing the legs around the robot's body.

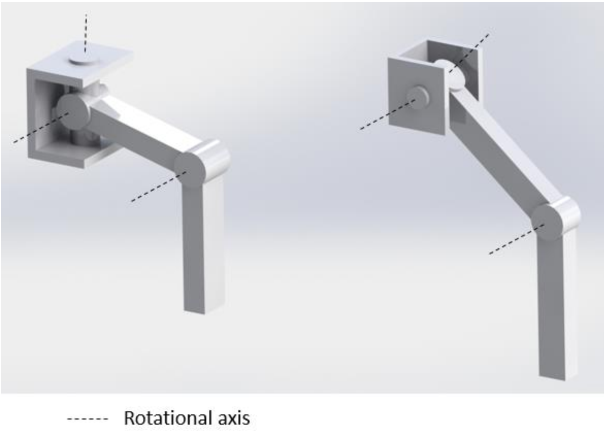

Figure 3: The left figure is a model of an insect-type leg configuration. The right figure is a model of mammal leg configuration.

In another study, Zhao, Sumioka, and Pfeifer (2011) used two motors to actively control the spine motion. The spine is constructed using deformable and rigid blocks. By removing deformable blocks at different positions, it creates a virtual joint. In addition, the flexibility and length of the spine can be adjusted according to the specification of the robot. A flexible spine is also used in biped robot to increase the degree of freedom of the torso, and the advantage of flexibility and variability (Mizuuchi, Inaba, & Inoue, 2001). The flexibility of the torso allows the robot to have various postures and better impact absorption when the robot falls. A simulation study also shows that a flexible spine increases travel distance and walking performance (Moore, McGowan, & McKinley, 2015).

A semi passive walking study is done by Omer, Ghorbani, Lim, and Atsuo Takanishi (2011). A passive compliance mechanism is added to ankle joint. The ankle has springs built-in to store and release energy during walking. By adjusting the stiffness of the ankle joint, semi-passive motion can be realized. When a robot is walking, there are impact and friction losses. In order to continuously walking on flat surface, actuators can be added to compensate the energy losses during walking. Passive walker Veronica uses series elastic actuator to control swing phase and stand phase of the passive walker (Van Ham, Vanderborght, Verrelst, Van Damme, & Lefeber, 2006). A study also shows that serial elastic actuators have several benefits such as shock tolerance, lower reflected inertia, more accurate and stable force control, less damage to the environment and energy storage (Hutter, Remy, Hoepflinger, & Siegwart, 2011; Pratt, 1995).

The difference between living organisms and robots is recoverability. Nevertheless, a true intelligent robot design emerges from the hardware and software designs. The hardware design fortifies the manoeuverability with resilient properties; the software design enhances the efficiency of actuation during locomotion.

Conclusion

This paper highlighted the importance of balanced consideration of morphology and controller of the robot, i.e. controller provides compliance of robot to the environment; morphology imparts resilient properties to cope with uncertain surrounding in order to minimize locomotion problems; conscious and subconscious judgment for decision making process. Nonetheless, there are a few problems to be solved as follows:

- The paradigm of efficient walker is missing, i.e. morphology, sensors, and controller requirement for locomotion.
- The optimization of legged robot locomotion in terms of perception, cognition and action.
- Materials usage and combination to alleviate locomotion problems such as stability, speed and energy expenditure.

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