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Realization of a legged locomotion system with innovative variable impedance actuators and experiments

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Executive Summary

This deliverable summarize the mechatronic design of the bipedal robot, realized by means of variable stiffness actuators by UT.

Contents

Chapter 1

Mechatronic Design of a Bipedal Walker with Compliant Leg

Leg compliance plays an important role in human locomotion, where it influences robustness, efficiency and walking speed. This influence has been qualitatively investigated using a bipedal spring-mass model, which has been shown to embody important features of human walking. In addition, it has been shown that varying the leg stiffness can greatly improve gait robustness. To facilitate further research in this direction, we present in this paper a robotic biped walker with variable leg compliance. The design of the walker aims to resemble the bipedal spring-mass model as closely as possible, and uses variable stiffness actuators to realize the variable leg compliance. Preliminary experimental results are presented, which validate the mechatronic design.

1.1 Introduction

Several different approaches in research of walking robots have been taken, but most aim at realizing human-like locomotion. The primary motivation for this is the desire to reproduce the robustness and efficiency that humans show in their walking.

McGeer introduced the concept of passive dynamic walking, where the mechanics of the walker is designed such that walking is a natural dynamic mode [1]. When started on a shallow slope, these machines settle into a steady gait, that does not require active control or energy injection. Robotic walkers based on the concept of passive dynamic walking can realize an energy efficiency comparable to that of humans [2]. However, this class of walkers is not very robust to external disturbances [3], but it was shown in [4] that introducing a small compliance in the legs can improve the robustness properties of this class of walkers.

Human walking on a flat surface can be accurately modeled by a passive planar bipedal spring-mass model [5]. More precisely, the model consists of two massless telescopic springs that resemble the legs, and a point mass at the hip. In this model, a gait is sustained by a continuous exchange of potential and kinetic energy between the springs and the mass. Essentially, the springs temporarily store kinetic energy and then release it again for push-off, much like humans do. The robustness of the gaits described by this model is significantly better than of the passive dynamic walkers, and this robustness and other gait properties are strongly related to leg stiffness [6].

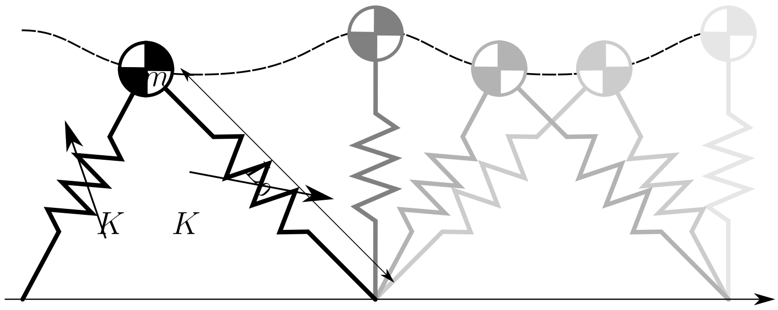

Figure 1.1: Ideal model of a bipedal walker with variable leg compliance—The model consists of massless telescopic springs, with a variable compliance K and a fixed rest length L_0, that represent the legs. The mass is concentrated in a point mass m at the hip joint.

The spring-mass model has been extended in [7, 8] to have a variable leg stiffness, as shown in Figure 1.1. The model consists of two telescopic springs representing the legs, each having a rest length L_0 and a variable stiffness K. A point mass m is situated in the hip. A control strategy was proposed to vary the stiffness of the springs as a reaction to perturbations. It was shown that the control strategy further improves robustness, indicating that introducing variable leg compliance to robotic walkers is a promising research venue.

In this work, we present the mechatronic design of a bipedal robot with variable leg stiffness, with the aim of facilitating further research on variable stiffness walking. The design of this robot tries to mimic the ideal model used in [4, 5, 7, 8] as closely as possible. Furthermore, the design incorporates a novel *variable stiffness actuator*, i.e., the vsaUT-II [9], realizing a large range of feasible leg stiffnesses.

The remainder of this paper is organized as follows. In Section 1.2 the requirements for the design are discussed. Section 1.3 presents a conceptual design satisfying these requirements. In Section 1.4 the mechanical design is presented, followed by an overview of the electronics in Section 1.5. The control software architecture is presented in Section 1.6. In Section 1.7 preliminary experimental results are presented, after which concluding remarks and an outline of future work is given in Section 1.8.

1.2 Requirements

The first step of the design process is to establish the elementary design requirements, which follow from the research purpose of the robot. The robot is to facilitate further research efforts in the direction taken by [5, 6, 7, 8], and therefore it is desired that the robot resembles the ideal model used in these works as closely as possible. From [8], the elementary properties of the model are summarized as follows:

- massless telescopic spring elements with variable stiffness representing the legs;
- a point mass at the hip;
- motion constrained to the sagittal plane.

These properties can be translated to the following set of requirements for the robot:

- *legs*: realize two telescopic spring elements, with variable stiffness, that can act as legs;

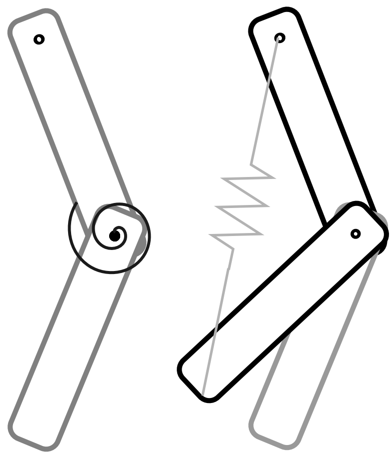

Figure 1.2: Realization of a telescopic spring element—By using two leg segments and a torsional spring element at the connecting joint, a virtual telescopic spring is realized between the extremal points.

- *weight distribution*: mass concentrated at the hip joint and light-weight legs;
- *constraints*: planar freedom in the sagittal plane.

In addition, the following requirements follow from practical considerations:

- hip joint actuation to control the swing leg motion;
- a leg retraction mechanism to avoid foot scuffing of the swing leg.

In Section 1.3 these requirements are translated into a conceptual design for the robot mechanics. The realization of the robot is then presented in Section 1.4.

1.3 Conceptual Design

The requirements presented in the previous Section can be translated into a conceptual design. In this Section, we discuss the important features of this concept.

1.3.1 Leg Design

The leg design has to meet four important requirements:

- the leg must realize telescopic spring behavior between the hip and the foot;
- the stiffness of this (virtual) spring element must be variable;
- the leg must be low weight, concentrating the mass as the hip;
- the leg must be retractable.

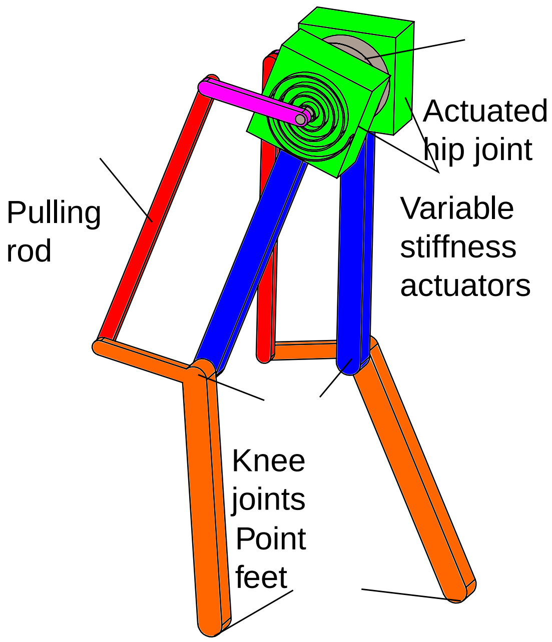

Figure 1.3: Conceptual design of the biped walker—The output of the variable stiffness actuator is coupled to the knee joint by a pulling rod, thus realizing the desired spring behavior of the legs.

Figure 1.2 illustrates the concept of a leg construction comprising an upper and lower leg segment and a torsional spring element at the joint connecting these segments (i.e. the knee). Such a construction realizes a virtual telescopic spring element between the extremal points, and at the same time the two segments facilitate leg retraction by active bending of the knee. By making the leg segments out of light-weight materials, the overall weight of the leg can be kept low.

The remaining requirement of having a variable leg stiffness can be satisfied by using a *variable stiffness actuator*. This class of actuators is characterized by the property that their apparent output stiffness can be varied independently from the actuator output position. By mounting the actuator near the hip joint and using a light-weight transmission to the knee joint, the requirements on the total weight distribution of the robot can be met.

Figure 1.3 presents an overview of the conceptual design of the robot, comprising two legs, each one with a variable stiffness actuator to realize the variable leg stiffness. A pulling rod is used to connect the output of the actuators to the knee joint. An actuated hip joint connects the two legs.

1.3.2 Supporting Frame

To constrain the motion of the robot to the sagittal plane, three solutions can be considered that have been proven effective in other research projects.

The first option is to give the robot four identical legs in parallel [10]. The inner two legs would act as the “left” leg, and the outer two legs as “right leg”, thus stabilizing the sideways motion of the robot. This solution allows the robot to walk forward without constraints, but significantly increases the design complexity.

A second option is to use a rotating support boom [11]. While the boom stabilizes the sideways motion of the robot, the robot is forced to walk in circles around the central rotation point of the boom. In order to minimize the effect of the curvature of this trajectory, the support boom must be long, which not only requires a lot of space but also might influence the robot dynamics due to its size.

Finally, a set of linear guides can be used to constrain the sideways motion of the robot [12]. A treadmill can be used to compensate for the forward robot motion, thus realizing a stationary setup. Because of its simplicity and considering available space for the setup, it is this solution that is chosen for this project.

1.4 Mechanical Design

Based on the conceptual design presented in Section 1.3, the final design is realized. Figure 1.4, on the next page, shows an overview of the realized design, with on the left a CAD drawing and on the right a photograph. Essentially, the robot consists of two identical leg assemblies that are connected by an actuated hip joint. In this Section, the details of the mechanical design are discussed.

1.4.1 Variable Stiffness Actuator

The most important component of the leg is the integration of a variable stiffness actuator. Various variable stiffness actuator prototypes, based on different concepts, have been proposed and realized [13, 14, 15, 16, 17]. The vsaUT-II [9] was chosen for this robot, because of its stiffness range (from nearly zero to nearly infinite stiffness) and its energy efficient design [18, 19].

The vsaUT-II internally uses the concept of a lever with a moving pivot to realize a variable output stiffness. This concept is depicted in Figure 1.5. Given two springs with fixed stiffness k and the lever length L, the output stiffness K is given by:

$$K := \frac{\partial F}{\partial x} = 2 \cdot k \cdot \left(\frac{q}{L - q} \right)^2 ,$$

where q is the pivot position with respect to the lever. It can be seen that for $q = L$ this concept realizes infinite stiffness, while for $q = 0$ zero stiffness is felt at the output. The motion of the pivot is actuated by a small motor, of which the output rotation is converted into a linear pivot motion along the lever via a $1:2$ planetary gear set.

The actuator output position x is changed by rotating the entire spring-lever assembly. It is noted that the output position only defines the equilibrium position of the actuator, and that a passive deflection can introduce a difference between this equilibrium position and the actual actuator output position.

The details of the working principles of the vsaUT-II can be found in [9]. A few modifications have been made with respect to the design presented therein, in particular to accommodate stiffer springs to support the total weight of the robot.

1.4.2 Leg Construction

In order to keep the legs light-weight, they have been constructed from carbon-fibre tubes. The modified vsaUT-II actuator is placed close to the hip joint, and connected to the knee

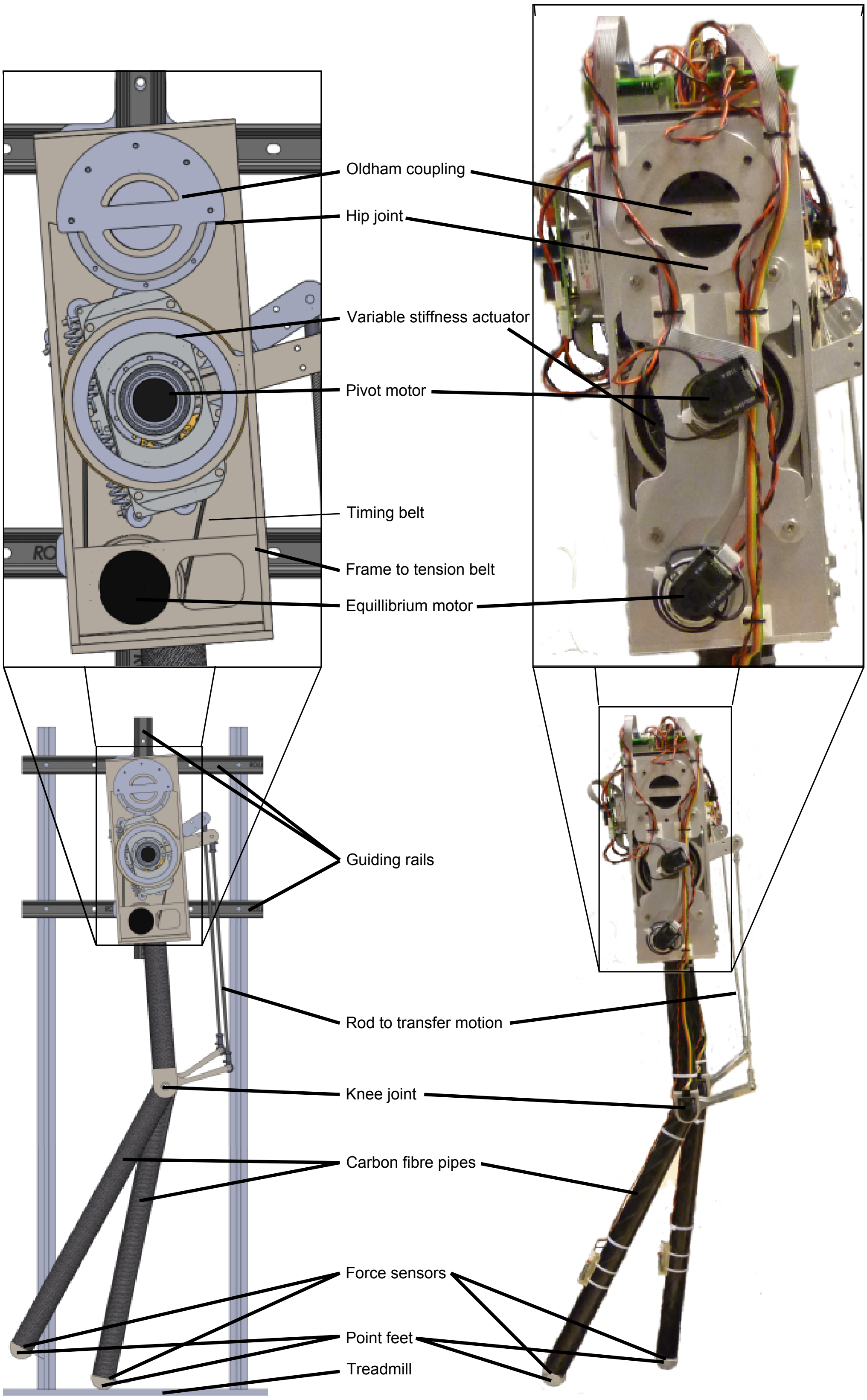

Figure 1.4: Mechanical design of the biped walker—On the left a CAD drawing is shown, and on the right a photograph of the realized robot.

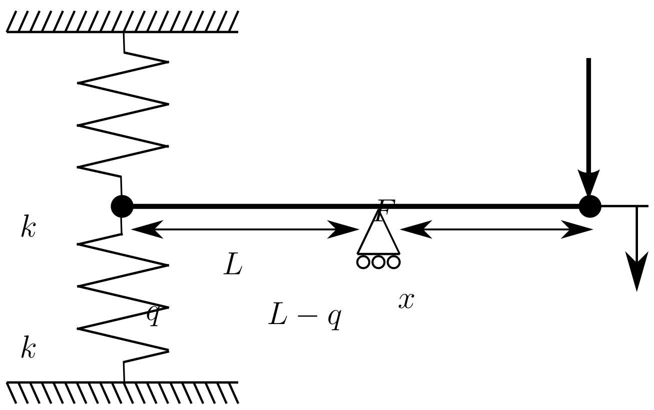

Figure 1.5: Realizing variable output stiffness—By varying the position of the pivoting point along the lever, the stiffness of the springs is felt differently at the output end of the lever.

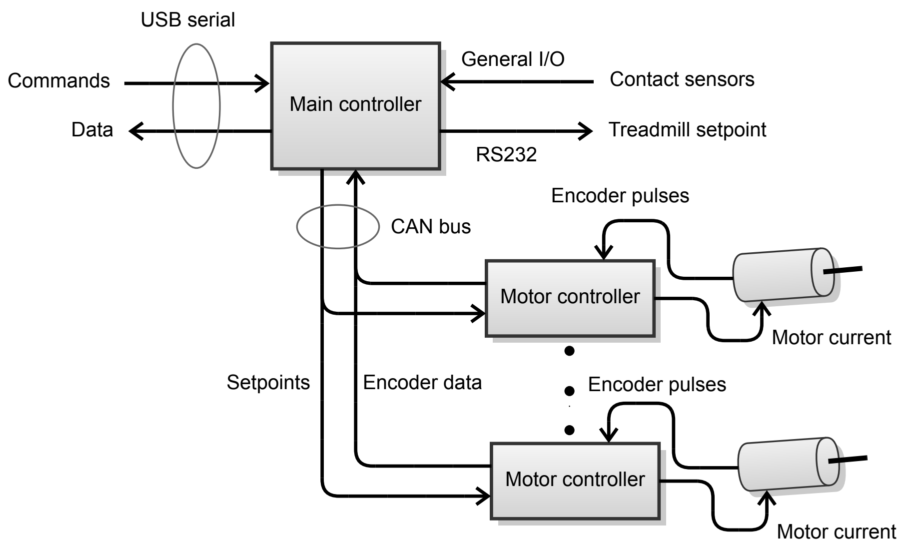

Figure 1.6: Overview of control system—The main controller acts on command inputs and sensor inputs received from the contact sensors and the motor controllers. The motor controllers take care of low level loop control.

by means of a pulling rod. In this configuration, the center of mass is kept close to the hip: when the leg is stretched to its maximum length of 1 m, the center of mass is at 0.19 m from the axis of rotation of the hip joint. The relative position of the center of mass may be changed by exchanging the carbon fiber tubes that comprise the upper and lower leg segments for segments of different lengths.

1.5 Electronics

In this Section the electronics of the robot are discussed. The main purpose is to illustrate the layered architecture design, shown in Figure 1.6. In the following, the various components of this architecture will be discussed.

1.5.1 Sensors

The robot is equipped with two types of sensors: contact sensors and position encoders. The contact sensors are located in the feet, and detect foot touchdown by means of a pressure sensor. A Schmidt trigger converts the signal of the sensor into a stable boolean signal that indicates whether the foot is in contact with the ground. This signal is relayed to the main controller, discussed hereafter, which can take control decisions based on this information.

All motors, i.e. the hip joint motor and the motors in the two vsaUT-II, are equipped with relative position optical encoders. In addition, the knee joints are equipped with relative position optical encoders, as well as the passive joint linking the robot to the linear guides that support the robot. In this way, the complete robot configuration can be known.

1.5.2 Motor Controllers

The motors are interfaced through Solo Whistle motor controllers from Elmo Motion Control. These motor controllers have an internal control loop that allows different modes of operation, including point-to-point motion and current control. In addition, the controllers provide an estimate of the joint velocities via numerical differentiation of the connected optical encoders, including auxiliary encoders (i.e. the encoders that are not directly connected to one of the motors).

A high-speed CAN interface connects the motor controllers to the high level controller. The use of the CAN bus allows fast operation, while at the same time reducing the overall complexity of the electronics.

1.5.3 Main Controller

The main controller runs the high level control software, discussed in Section 1.6. It is realized by an mbed NXP LPC1768. This platform is based on a powerful ARM Cortex-M3 MCU, and provides the necessary interfaces. In particular, it provides the CAN interface required to interface the motor controllers, an RS232 interface to communicate with the treadmill, a USB interface to communicate with an auxiliary monitoring PC, and general digital I/O to interface the contact sensors in the feet.

1.6 Software Architecture

In this Section, the architecture of the high level control software is discussed. This controller is implemented as a state machine, as shown in Figure 1.7 on the next page. The state transitions are triggered either by commands send to the main controller via USB, or, during walking, by the signals from the foot contact sensors. If abnormal sensor values or a failure of one of the electrical components is detected, the state machine will enter into the error state, in which all motor controllers are turned off for safety.

The first few states in the diagram concern the initialization of the motor controllers and the main controller:

- *Idle*: When the main controller has booted, it waits in this state, where all motor controllers are switched off.

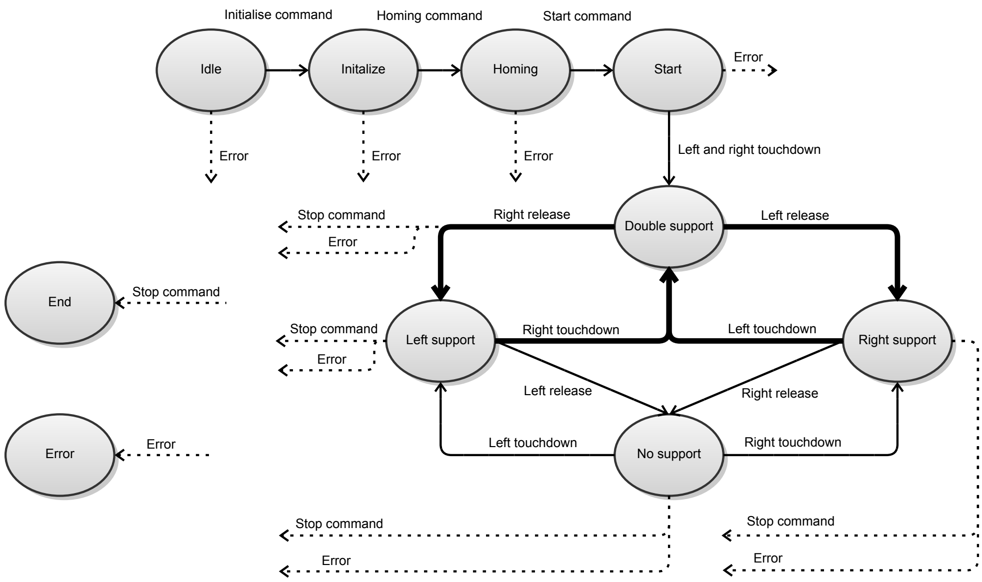

Figure 1.7: Control software architecture—The high level control of the robot is implemented as a state machine. The thick lines indicate the gait transitions during nominal walking.

- *Initialize*: After received the appropriate external command, the motor controllers are configured by the main controller by loading relevant parameter values.
- *Homing*: In this state, the range of motion of the joint is determined in order to calibrate the relative position encoders.
- *Start*: This state is the starting point for starting the gait.

The state transitions between these states are triggered by commands sent to the main controller via USB.

After this initialization phase, the robot is ready to enter into a gait pattern. During a gait, the robot alternates between standing on the left (*Left support*) and right (*Right support*) leg, with an intermediate double support phase (*Double support*), where both feet are in contact with the ground. The transitions between these states are dictated by the foot contact sensors. In each state, a particular control strategy generates set-points for each motor.

It may happen that the robot briefly loses ground contact with both feet, which cause the system to transition trough the *No support* state. However, nominally the state machine should adhere to the flow indicated by the thick lines. This flow can be stopped at any time by sending a stop command to the main controller via USB.

1.7 Preliminary Experimental Results

In this Section, preliminary experimental results are presented. In particular, two experiments were performed to validate the mechatronic design, which are outlined in the following. The accompanying movie presents video footage of the experiments.

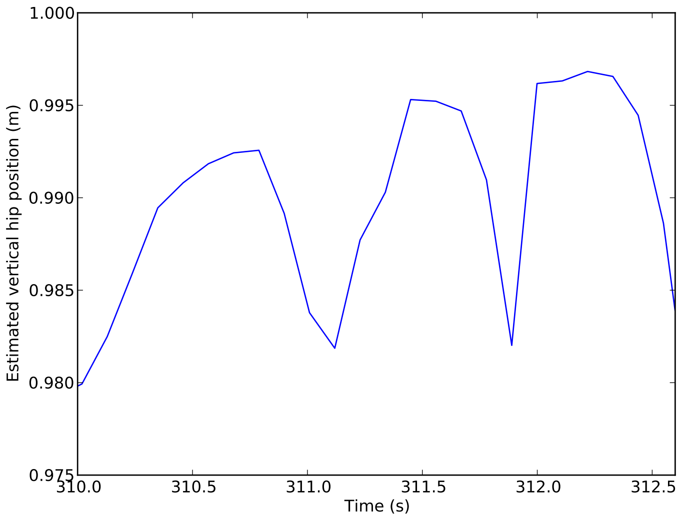

Figure 1.8: Walking with rigid legs—The hip trajectory show the characteristic properties of a compass gait.

1.7.1 Walking with Rigid Legs

Essentially, the compass gait walker can be considered as a walker with compliant legs, where the stiffness is set to infinity. In order to test the software architecture and sensors, this gait was first tested on the robot. This was done by setting the variable stiffness actuators to their maximum stiffness setting, and the implementation of a simple leg swing and retraction algorithm. This algorithm retracts the swing leg as soon as the foot loses contact with the ground, after which the leg is swung forward and, extended again just before the foot touching down.

In the movie, it is shown that with this algorithm the robot can walk over longer periods of time. Figure 1.8 shows a fragment of the estimated hip trajectory, which has been calculated from measured encoder data. It can be seen that the hip trajectory indeed shows the characteristics of a compass walker with rigid legs. In particular, note the abrupt direction changes of the hip at foot impact.

1.7.2 Walking with Compliant Legs

Following up on the previous experiment, the leg stiffness was set to a constant value of 3500 N/m. It is emphasized that this means that the apparent output stiffness of the variable stiffness actuator is controlled such that a constant stiffness is realized for the virtual spring element between the hip and foot, as shown in Figure 1.2. The same basic leg swing and retraction algorithm was used as in the previous experiment.

The movie shows that this gait is not as stable as the gait with rigid legs, indicating that a more sophisticated control strategy is required. However, the results are sufficient to illustrate the difference between walking with rigid and compliant legs. Looking at Figure 1.9, it can be seen that the hip trajectory no longer shows the abrupt direction changes observed in walking with rigid legs. Instead, we see a trajectory that takes a more sinusoidal shape, which is expected from theory [5]. Moreover, the step time is also longer

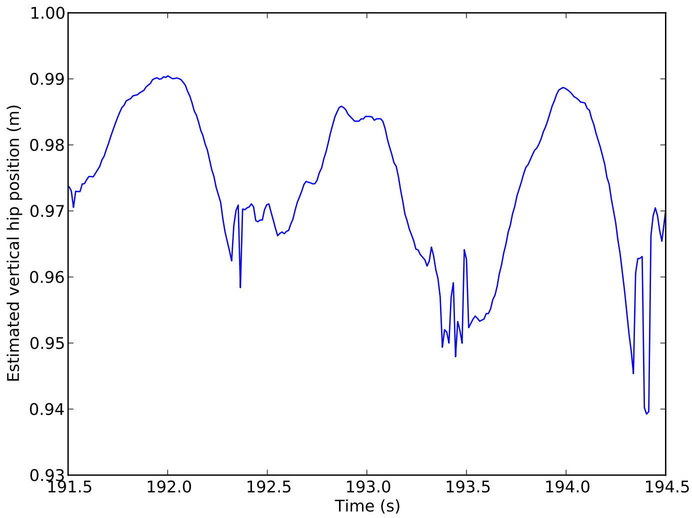

Figure 1.9: Walking with compliant legs—The hip trajectory starts to look more sinusoidal, as was expected from theory. The step time is also longer when compared to the gait with rigid legs.

for each step, when compared with the gait with rigid legs.

1.8 Conclusions and Future Work

In this paper, the design of a robotic bipedal walker with compliant legs was presented. The design incorporates a novel variable stiffness actuator, which allows the leg compliance to be varied. Preliminary experiments were performed to show that the robot can walk with both rigid legs and compliant legs.

The robot will be used to investigate control strategies for bipedal locomotion with compliant legs. The first step in this investigation will be the validation of the control strategy presented in [7, 8]. After this, further improvements in variable stiffness walking can be investigated by developing new control strategies focussing more on robustness and energy efficiency, and validating them on the robot.

Bibliography

[1] T. McGeer, “Passive dynamic walking,” *International Journal of Robotics Research*, vol. 9, no. 2, pp. 62–82, 1990.

[2] S. Collins, A. Ruina, R. Tedrake, and M. Wisse, “Efficient bipedal robots based on passive-dynamic walkers,” *Science*, vol. 307, no. 5712, pp. 1082–1085, 2005.

[3] M. Garcia, A. Chatterjee, A. Ruina, and M. Coleman, “The simplest walking model: Stability, complexity, and scaling,” *Journal of Biomechanical Engineering*, vol. 120, no. 2, pp. 281–288, 1998.

[4] M. Jafarian, G. van Oort, R. Carloni, and S. Stramigioli, “Performance comparison of a planar bipedal robot with rigid and compliant legs,” in *Proceedings of the IFAC World Congress*, 2011.

[5] H. Geyer, A. Seyfarth, and R. Blickhan, “Compliant leg behaviour explains basic dynamics of walking and running,” *Proceedings of the Royal Society B*, vol. 273, no. 1603, pp. 2861–2867, 2006.

[6] J. Rummel, Y. Blum, and A. Seyfarth, “Robust and efficient walking with spring-like legs,” *Bioinspiration and Biomimetics*, vol. 5, no. 4, p. 046004, 2010.

[7] L. C. Visser, W. de Geus, S. Stramigioli, and R. Carloni, “Human-like walking with compliant legs,” in *4th International Workshop on Human-Friendly Robotics*, 2011.

[8] L. C. Visser, S. Stramigioli, and R. Carloni, “Robust bipedal walking with variable leg stiffness,” submitted to the IEEE International Conference on Biomedical Robotics and Biomechatronics, 2012.

[9] S. S. Groothuis, G. Rusticelli, A. Zucchelli, S. Stramigioli, and R. Carloni, “The vsaUT-II: a novel rotational variable stiffness actuator,” in *Proceedings of the IEEE International Conference on Robotics and Automation*, 2012.

[10] E. Dertien, “Dynamic walking with Dribbel,” *IEEE Robotics and Automation Magazine*, vol. 13, no. 3, pp. 118–121, 2006.

[11] K. Sreenath, H.-W. Park, I. Poulakakis, and J. Grizzle, “A compliant hybrid zero dynamics controller for stable, efficient and fast bipedal walking on MABEL,” *International Journal of Robotics Research*, vol. 30, no. 9, pp. 1170–1193, 2010.

[12] B. Verrelst, R. van Ham, B. Vanderborght, F. Daerden, and D. Lefeber, “The pneumatic biped “LUCY” actuated with pleated pneumatic artificial muscles,” *Autonomous Robots*, vol. 18, no. 2, pp. 201–213, 2005.

[13] R. Schiavi, G. Grioli, S. Sen, and A. Bicchi, "VSA-II: A novel prototype of variable stiffness actuator for safe and performing robots interacting with humans," in *Proceedings of the IEEE International Conference on Robotics and Automation*, 2008.

[14] S. Wolf and G. Hirzinger, "A new variable stiffness design: Matching requirements of the next robot generation," in *Proceedings of the IEEE International Conference on Robotics and Automation*, 2008.

[15] O. Eiberger, S. Haddadin, M. Weis, A. Albu-Schäffer, and G. Hirzinger, "On joint design with intrinsic variable compliance: Derivation of the DLR QA-joint," in *Proceedings of the IEEE International Conference on Robotics and Automation*, 2010.

[16] A. Jafari, N. G. Tsagarakis, B. Vanderborght, and D. G. Caldwell, "AwAS-II: A new actuator with adjustable stiffness based on the novel principle of adaptable pivot point and variable lever ratio," in *Proceedings of the IEEE International Conference on Robotics and Automation*, 2011, pp. 4638–4643.

[17] B.-S. Kim and J.-B. Song, "Hybrid dual actuator unit: A design of a variable stiffness actuator based on an adjustable moment arm mechanism," in *Proceedings of the IEEE International Conference on Robotics and Automation*, 2010.

[18] L. C. Visser, R. Carloni, and S. Stramigioli, "Energy efficient variable stiffness actuators," *IEEE Transactions on Robotics*, vol. 27, no. 5, pp. 865–875, 2011.

[19] R. Carloni, L. C. Visser, and S. Stramigioli, "Variable stiffness actuators: a port-based power flow analysis," *IEEE Transactions on Robotics*, vol. 28, no. 1, pp. 1–11, 2012.