Body Balancing Control of A Six-Legged Robot SiLVIA

Han Wang, Jingwen Zhang and Junjie Shen

Abstract— **With the robot SiLVIA (Six Legged Vehicle with Intelligent Articulation) built in Romela Lab, we achieve the function of balancing the body at various operating conditions (standing, wall climbing, etc.) by implementing robotic motion control. Decentralized control with position feedback for each joint is used to control 18 joints. Decentralized feedforward compensation is tested to improve the performance of whole system. Experiment result is showed at the end.**

I. INTRODUCTION

Effective and reliable robotic delivery systems for handling intermittent, on-demand, or scheduled deliveries of items in a wide variety of environments are needed. Ideally, delivery robots should be able to securely carry objects and remain stable while moving, and have a configuration that prevents object damage or loss. Due to various types of environment during the delivery task, the robotic system will require built-in redundancies to deal with risks. A natural choice for redundancies is a hexapod as it is a good tradeoff between stability and speed. If a tripod gait is used, the robot will be able to walk fast while still maintain static stability at all times. This allows it to navigate through highly uneven terrains even if open-loop control is used. Furthermore, the hexapod effectively could be turned into a quadruped robot if one or two legs fail, allowing the robot to continue to operate with damaged legs.

SiLVIA developed at RoMeLa is a good candidate for this kind of application as shown in Figure 1. With 18 degrees of freedom and a yaw-pitch-pitch kinematics scheme, current SiLVIA can deftly maneuver through uneven terrain with open-loop control being used. To make it more compatible with the requirements, close-loop control for 3-axis stance and 3-axis position is needed. It is the base function for delivery system to carry objects while moving [1]. As we all know, humans can keep a cup of water always balance while standing in any pose, walking and even running. As for delivery robotic systems, a most representative scenario is that one cup of coffee is scheduled to be delivered to customers where the robot should be able to prevent the drinks from any disturbance (significant vibration or tilt) no matter it is carried by the end-effector or the body. Both SpotMini from Boston Dynamics and Laikago from Unitree possess this capability [2].

Based on the signal of IMU on the body of SiLVIA, robot control algorithms that uses sensory feedback in closed-loop form will be used to perform this functional behavior. The SiLVIA will stand on a unstable plate which is used to simulate the external disturbances applied to the whole system. By detecting changes in pitch, roll and yaw from IMU, position controller will response to these disturbances quickly and reject them to keep the body totally balance with a tiny tolerance.

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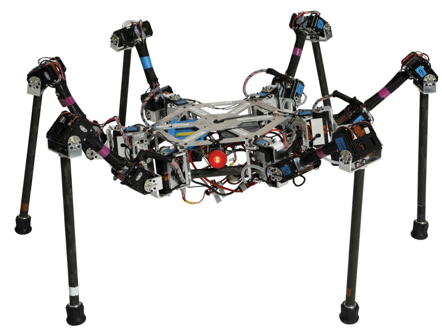

Fig. 1. Genral configuration of SiLVIA

II. OBJECTIVES

To implement the function of stabilizing central body at various operating conditions, real-time closed-loop control of SiLVIA is supposed to be used. A mini PC is used as both host and target. An IMU attached on robot central body frame is also connected with PC to feedback real-time attitude information of body. At the same time, PC generates and sends out control signal to all 36 motors with RS-485 serial communication.

When 6 feet of hexapod robot are fixed on the moving table, hexapod robot could be assumed as a parallel robot. To achieve the control objective, motion control at joint space based on inverse kinematics is suitable. Considering the gear ratio over 200 of each motor, decentralized control with position and attitude feedback from IMU is used to kill disturbance.

The quantized objective of control could be set as yaw angle and roll angle always less than 10 degree while swing the table. However, because of the physical performance limitation of motor and control loop, if we give a disturbance with too high frequency or amplitude, an error in excess of 10 degree will inevitably appear no matter what controller is used.Decentralized feedforward compensation is also planned to improve the control performance while keep body steady while climbing the wall.

III. HARDWARE SETUP

The project will be based on the SiLVIA, a powerful mid-sized hexapod robot developed at RoMeLa (Robotics & Mechanisms Laboratory). SiLVIA spans 1 m x 1 m x 0.2 m, and weighs 10 kg. Comprised of one central body frame with six 3DOF limbs, SiLVIA utilizes thirty-six Dynamixel MX-106 motors in pairs at each joint. The stall torque for each motor pair is approximately 25.0 Nm. SiLVIA can carry a 5 kg payload while walking or can lift 25 kg payload while standing with a battery life of 2 hours under normal operation. The ripple gait, which picks up one leg each time, the amble gait, which picks up two leg each time, and the tripod gait, which picks up three leg each time, can be chosen depending on the required speed and payload [3]. Furthermore, a real time motion planner based on nonlinear trajectory optimization was developed to navigate over uneven terrain. Because of gearbox with gear ratio 225:1, the decentralized control can be used.

Each limb is composed of 3 degrees of freedom in a yaw-pitch-pitch kinematics scheme and each joint is controlled by a pair of Dynamixel MX-106 motor, which is a high performance actuators with a fully integrated DC (Direct Current) motor, reduction gearhead, controller, driver and network, all in one servo module actuator [4]. And the pair of motors are connected through synchronized port to make sure that they rotate synchronously. The MX-series actuator of Dynamixel contains a new contactless magnetic rotary encoder for accurate angular movement over a full 360 degrees. The absolute angle measurements provide instant and reliable information of the angular position with a resolution of 12 bits = 4096 positions within 360 degrees. This delivers fine angle movements accurate to 0.088 degrees. The MX-series also integrates a new PID Control, which automatically and accurately corrects for naturally occurring errors such as backlash (caused by small gaps in the gears). Thus, positioning is more reliable and in compliance to specifications.

IV. KINEMATICS ANALYSIS

A. Problem Statement

For our application, we are most interested in the body motions while theoretically fixing the end-effectors of the six legs to the ground. The body motions are essentially achieved by moving the legs relatively. For example, if we want SiLVIA to do a body translation along z-axis in the world frame, the motion can be directly passed to the six legs and the end-effectors of the six legs should move with the same translation in the body frame. The same principle goes for body rotations and their combinations. Therefore, leg kinematics is necessary for achieving the designed body motions. Specifically, leg forward kinematics is used to compute the initial positions of the end-effectors while leg inverse kinematics is used to calculate the new joint angles if the body is moving. Fig. 2 show the frame attachment. Note that our goal is to keep the body frame fixed in the world frame, so we can just set the body frame as the world frame for simplicity.

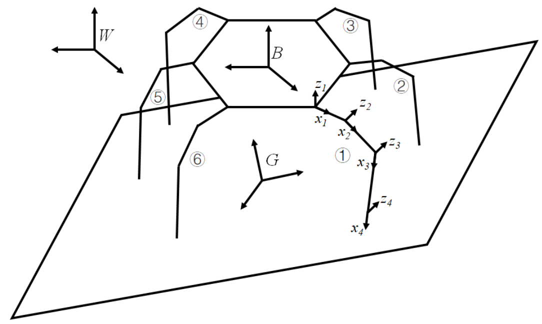

Fig. 2. Frame attachment.

B. Leg Forward Kinematics

Table 1 shows the modified Denavit-Hartenberg parameters of Leg j $(j = 1,2,3,4,5,6)$ from body frame to end-effector frame.

TABLE I

MODIFIED DENAVIT-HARTENBERG PARAMETERS OF LEG j.

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	a_0	0	θ_{j1}
2	$-\pi/2$	a_1	0	θ_{j2}
3	0	a_2	0	θ_{j3}
4	0	a_3	0	0

Therefore, the forward kinematics of Leg j is determined to be

$$ {}^{B}_{4}T_j = {}^{B}_{1}T_j \; {}^{1}_{2}T_j \; {}^{2}_{3}T_j \; {}^{3}_{4}T_j, \tag{1}$$

where

$$
\begin{aligned}
T_{11} &= \cos\theta_{j1}\cos\left(\theta_{j2}+\theta_{j3}\right),\\
T_{12} &= -\cos\theta_{j1}\sin\left(\theta_{j2}+\theta_{j3}\right),\\
T_{13} &= -\sin\theta_{j1},\\
T_{14} &= a_0+\cos\theta_{j1}\left[a_1+a_2\cos\theta_{j2}+a_3\cos\left(\theta_{j2}+\theta_{j3}\right)\right],\\
T_{21} &= \sin\theta_{j1}\cos\left(\theta_{j2}+\theta_{j3}\right),\\
T_{22} &= -\sin\theta_{j1}\sin\left(\theta_{j2}+\theta_{j3}\right),\\
T_{23} &= \cos\theta_{j1},\\
T_{24} &= \sin\theta_{j1}\left[a_1+a_2\cos\theta_{j2}+a_3\cos\left(\theta_{j2}+\theta_{j3}\right)\right],\\
T_{31} &= -\sin\left(\theta_{j2}+\theta_{j3}\right),\\
T_{32} &= -\cos\left(\theta_{j2}+\theta_{j3}\right),\\
T_{33} &= 0,\\
T_{34} &= -a_2\sin\theta_{j2}-a_3\sin\left(\theta_{j2}+\theta_{j3}\right),\\
T_{41} &= 0,\\
T_{42} &= 0,\\
T_{43} &= 0,\\
T_{44} &= 1,
\end{aligned}
$$

are the elements of the 4×4 homogeneous transform matrix ${}^{B}_{4}T_j$ from the body frame to the end-effector frame of Leg j.

C. Leg Inverse Kinematics

Leg inverse kinematics is solved using geometric approach shown in Fig. 3. Note that theoretically there are 4 different solutions but we only choose this one (black) for our application, which is the closest one to the initial configuration. First, θ_1 is determined to be

$$\theta_1 = \operatorname{atan2}\left(p_y, p_x - a_0\right). \tag{2}$$

Second, θ_2 is determined by ϕ_1 and ϕ_2 as

$$\theta_2 = \frac{\pi}{2} - \phi_1 - \phi_2. \tag{3}$$

ϕ_1 is determined to be

$$\phi_1 = \operatorname{atan2}\left(l, -p_z\right), \tag{4}$$

where

$$l = \sqrt{\left(p_x - a_0 - a_1 \cos\theta_1\right)^2 + \left(p_y - a_1 \sin\theta_1\right)^2}, \tag{5}$$

and

$$\phi_2 = \arccos\frac{a_2^2 + d^2 - a_3^2}{2a_2 d}, \tag{6}$$

where

$$d = \sqrt{l^2 + p_z^2}. \tag{7}$$

Finally, θ_3 is determined to be

$$\theta_3 = \pi - \arccos\frac{a_2^2 + a_3^2 - d^2}{2a_2 a_3}. \tag{8}$$

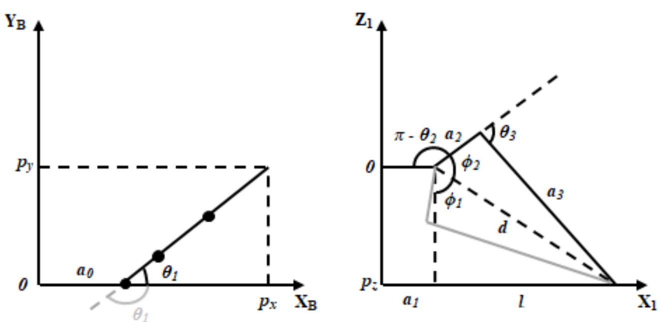

Fig. 3. Geometric approach.

V. SIMULATION

To check whether the designed methodology is correct for our application, a MATLAB simulation with animation will be conducted, shown in Fig. 3. Specifically, given a change of the terrain $T(t) \in \mathbb{R}^{4\times 4}$, where $T(t)$ is the homogeneous transform matrix from the world frame to the ground frame, the time history of the position of each end-effector can be calculated as $T(t)p_o$, where p_o is the initial position vector. Then, using leg inverse kinematics, the time history of the joint angles can be computed. Note that $T(t)$ can be obtained using the proposed IMU sensor and joint angle information can be also collected from the embedded encoders. Fig. 4-9 show how SiLVIA responds to the change of the terrain in order to keep the body frame stable.

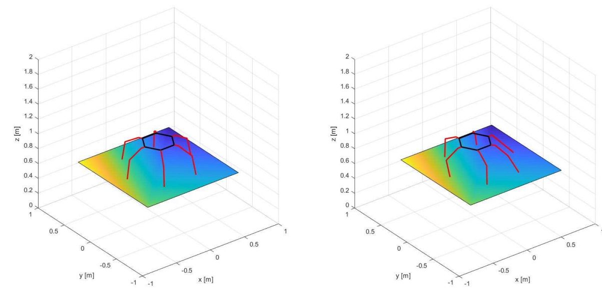

Fig. 4. Ground translation along x-axis.

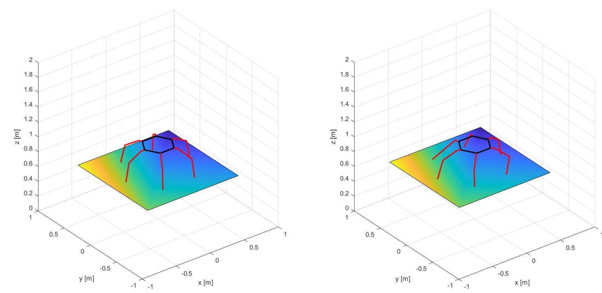

Fig. 5. Ground translation along y-axis.

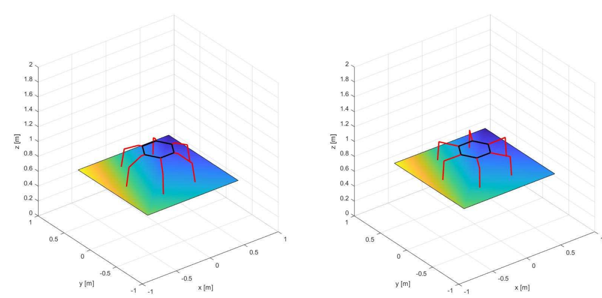

Fig. 6. Ground translation along z-axis.

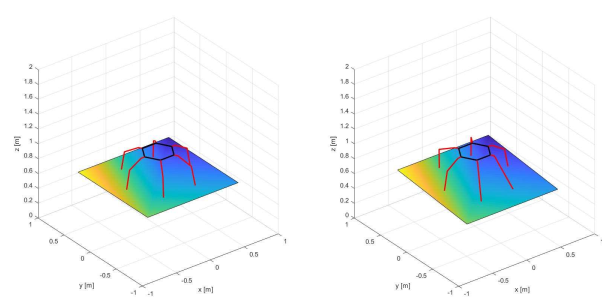

Fig. 7. Ground rotation along x-axis.

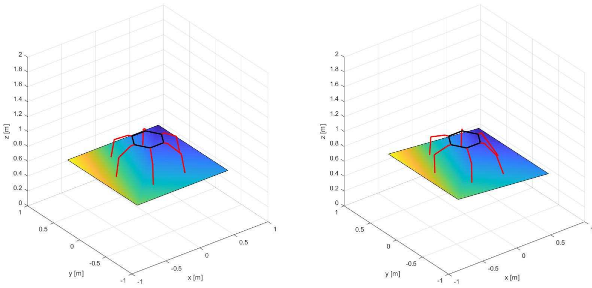

Fig. 8. Ground rotation along *y*-axis.

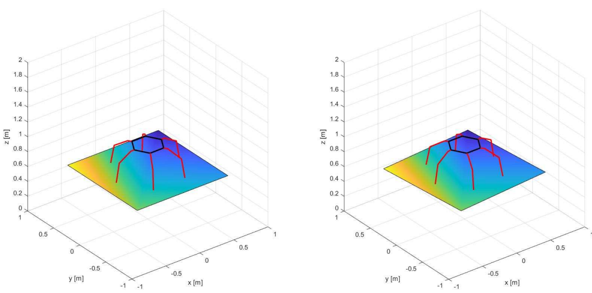

Fig. 9. Ground rotation along *z*-axis.

VI. CONTROLLER DESIGN

Based on the kinematics analysis of body balancing, the control task can be divided into two parts. One part is to ensure that joints of SiLVIA to reach goal positions with desired characteristics given the goal positions, which can be seen as an inner loop controller.And another part is to generate the time history of the goal positions, that is the desired trajectory based on the body orientation disturbance which can be seen as an outer loop controller. Controller design are based on these two parts. And the inner loop controller is using decentralized control to achieve motion control precisely while the outer loop is using PID control to stabilize the overall system and achieve desired transient response.

A. Motor Controller

Due to the high gear ratio of the servo motor Dynamixel MX-106R used for SiLVIA, the coupling effects between joints due to varing configurations during motion can be treated as disturbance inputs. Under this circumstance, decentralized control strategy can be used where each joint axis is controlled as a single-input/single-output system [5]. Based on this strategy, the simplest control structure for each servo motor is the controller with position feedback as shown in Figure 10. In this controller, proportional gain K_p and integral gain K_r are used. The proportional gain K_p is used to acquire a large gain to achieve an effective rejection of the disturbance while the integral action is to avoid steady state error which ensure the motor's precision.

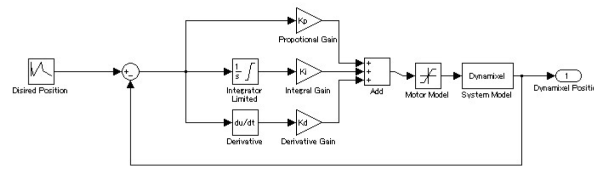

Fig. 10. Block shceme of drive control with position feedback

In addition to the previous motor controller, another controller is used to achieve better tracking when it involves high values of motor speed and acceleration. On the basis of controller with position feedback, a decentralized feedforward compensation is added to reduce the tracking error. The position feedback control with the decentralized feedforward compensation [5] which plans ahead for the desired values of velocity and acceleration is shown in Figure 11.

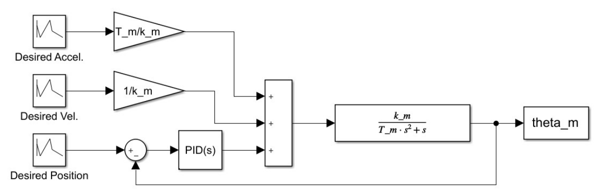

Fig. 11. Block shceme of position feedback control with decentralized feedforward compensation

Based on these two control structures for the servo motor, 1Hz sine wave is used as reference input to compare these two motor controllers. Figure 12 shows the tracking results of different controllers. Two controllers use identical PID gains $K_p = 8.0$, $K_i = 5.0$ and $K_d = 0$ which are determined through MATLAB PID tunning tool.

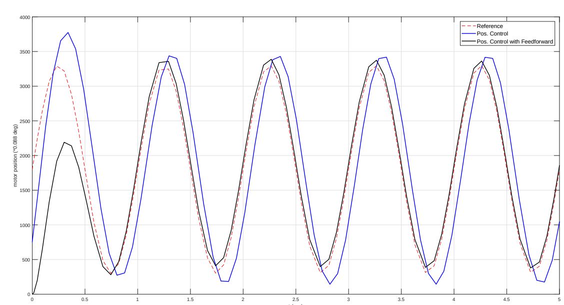

Fig. 12. 1Hz sine wave tracking of different position feedback controllers

From the result, we can see that position feedback controller without feedforward action results in phase lag compared to the reference input. With feedforward action, the controller shows better tracking result. Feedforward action provides a better prediction for the desired trajectory with regards to position, velocity and acceleration. Given a specific task, different motor controller will be used considering the motor speed and acceleration required for the task.

B. *High-level Closed-loop Controller*

For body balancing control, a outer loop based on the feedback of IMU (Inertial Measurement Unit) is added to achieve real-time closed-loop control of SiLVIA's body orientation. The detailed block scheme is shown in Figure 13. The inner loop controller for the servo motor described in the previous chapter is embedded in the block "*Motor_Controller*".

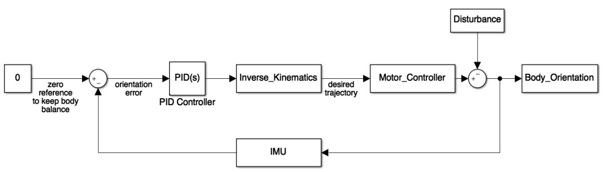

Fig. 13. Block shceme of high-level body balancing control

Zero reference inputs which are only composed of roll and pitch angles are used to indicate that the control goal is to keep the body balancing. Yaw angle is not treated because it is not related to balancing of the body. Then based on the feedback signal of IMU which is mounted on the body center, orientation error can be calculated as the control input. Desired trajectory is generated using the method described in the chapter "Kinematics Analysis". Each motor tracks this trajectory through motor controller so as to compensate any orientation error which is mainly from the external disturbance.

Besides the controller design parameters K_p, K_i and K_d that used in motor controller, another PID controller is used in the outer loop to stabilize the overall system. In this PID controller, another set of proportional gain, integral gain and derivative gain is used which includes K_{po}, K_{io} and K_{do}. The proportional gain K_{po} is used to achieve a high disturbance rejection factor and also achieve rapid response, the integral gain K_{io} is mainly used to avoid steady state error while the derivative gain K_{do} is used to improve the transient response.

VII. IMPLEMENTATION

Main goal of the implementation to verify the previous controller design and achieve practical function for applications. Two kinds of situations are used to do the verification. One is when SiLVIA is standing in an unstable slab as shown in Figure 14. The force between the leg and the slab is due to gravity and the leg tip's position is fixed assuming no sliding. Under this circumstance, this task can be thought as free motion control. Another is when SiLVIA is climbing wall as shown in Figure 14. SiLVIA is having strong interactions with the wall because the leg needs to push against the wall to generate large friction to hold the body. This task needs to be though as constrained motion control.

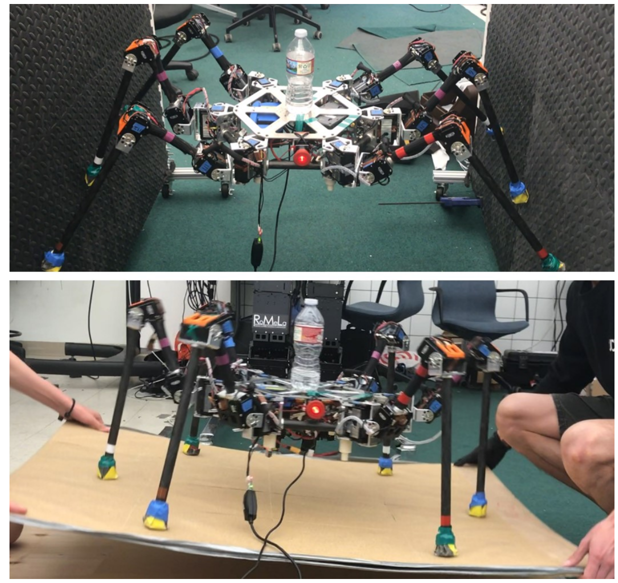

Fig. 14. Implementation when SiLVIA is standing (down) and when SiLVIA is climbing wall (upper)

A. *Standing*

1) Result: A water bottle is placed on the body to show the capability of keeping items stable which is important to accomplish real delivery tasks. The PID gains for the inner motor controller are already stated in the Chapter "Controller Design". The PID gains for the outer loop controller are designed to achieve a reasonable performance.

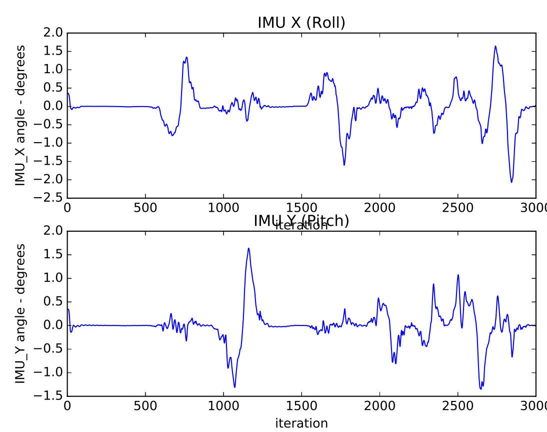

Fig. 15. Time history of roll angle and pitch angle of SiLVIA's body

At the beginning of gain tuning, proportional gain K_{po} is increased from 0.0 to the largest value which can stable the system without the addition of integral and derivative actions. Then proper integral gain K_{io} is added to remove the steady state error completely without generating too many oscillations. Finally, derivative gain K_{do} is added to improve transient response, especially the rising time. The final gains used to implement are $K_{po} = 0.1$, $K_{io} = 0.1$ and $K_{do} = 0.05$. The real time roll and pitch angles of SiLVIA's body are recorded in Figure 15 (each iteration indicates 10ms). Errors are within $\pm 2^\circ$ and the water bottle can be kept stable.

2) Discussion: In this operating condition, the disturbance could be in high frequency which depends on how fast operators move the bottom slab and SiLVIA needs to compensate the error quickly. This involves high acceleration and high speed for motors so that position feedback controller with decentralized feedforward compensation is chosen for the motor controller. Oscillation is still existing which can be found from the real-time error. The outer loop PID gains are still needed to be optimized to cancel it.

B. Wall Climbing

1) Result: SiLVIA is capable of climbing wall in a tripod-gaits manner [3]. The water bottle is still used to indicate the practical functionality. Without the body balancing controller, the body orientation error accumulates step by step and the water bottle falls down when the error reaches a threshold value. It also has influence on the stability of climbing because as the changes of body orientation without compensation, the center of gravity leans forward or backward so that some of the legs cannot generate enough friction to hold the weight of the robot. With the body balancing controller, SiLVIA can climb the wall greatly and carry the water bottle upside stably. The controller design parameters are the same as ones used in the standing case. The real-time roll angle of SiLVIA's body is recorded to discuss the performance of the controller as shown in Figure 16 (each iteration indicates 10ms). The maximum error can reach 6°.

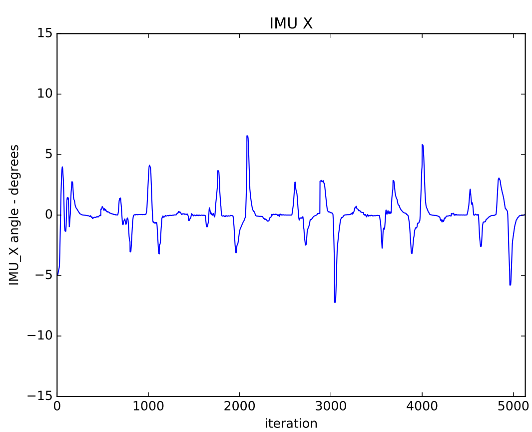

Fig. 16. Time history of roll angle of SiLVIA's body during wall climbing

2) Discussion: Although the controller design parameters used are unchanged during wall climbing, motor controller used is different. Because SiLVIA is designed to climb the wall in a very small speed currently, position feedback controller is enough for this application. Due to the constrained motion during wall climbing, the oscillation is obviously reduced even with the same controller design parameters.

VIII. FUTURE WORKS

From the implementation results, balancing performance still has some room for improvement. Especially, the maximum error can reach 6° when the SiLVIA is having strong interactions with the environment, like the wall. Advance controllers considering the robot dynamics, such as inverse dynamics control, impedance control and force/motion hybrid control, can be investigated and better balancing performance should be expected. For SiLVIA, the derivation of the dynamic model is similar to the manipulator case, the main difference being the presence of nonholonomic constraints on the generalized coordinates [5]. The Lagrange formulation can be used. To some extent, the body balancing controller can used to keep the body in any desired orientation. During delivery tasks, items are expected to be hold horizontally. When it comes to dynamic manipulation, other desired orientation will be expected to achieve specific applications. A robotic arm mounted on the SiLVIA's body is developing currently for dynamic manipulation. With the addition of the robotic arm, controllers need to be modified for different applications.

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APPENDIX

A. Itemized breakdown of team members

a) Han Wang: Python coding, IMU sensor testing and the outer loop controller design.

b) Jingwen Zhang: Encoder testing, servo motor communication, Python coding, the overall system controller design, and implementation testing.

c) Junjie Shen: Kinematics analysis, MATLAB simulation, Python coding, the outer loop controller design.

B. Bill of materials

SiLVIA is a six-legged robot developed at RoMeLa (Robotics and Mechanisms Laboratory) and this project is only using this existing robotic platform. There is no other cost.