Dynamics and control of a 6-dof biped robot on Matlab/SimMechanics

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Abstract. This paper plans to demonstrate a biped robot on Matlab/SimMechanics, which tackles dynamics problems with time efficient numerical models. Biped robot model has 7-links and all the joints connecting links are revolute in nature. Two identical legs have hip joints between upper leg and torso, knee joints between the lower leg and upper leg parts, ankle joint between the lower leg and foot. A rigid body forms the torso. Modelling of ground contact forces is done using inbuilt Matlab contact library. A PID controller is used in order to simulate the dynamics of the system. Results obtained from the dynamic simulation are presented.

Keywords: Biped Robot , SimMechanics , Dynamic Modelling , Control

1 Introduction

In the most recent couple of decades objective of copying human movement through strolling biped robots has gotten huge consideration among scientists. Biped robots can move in obscure landscapes, climb staircases which wheeled robots are unfit to perform. They can be employed in hazardous works such as rescue operations [5], disaster situation[1] or rehabilitation of disabled people for example, dynamically controlled prosthetics [10]. Made humanoid and biped, to rescue injured victims into safety they can prevent human life from being put to danger. Due to the complexity of human walking, which increases with the increase of no of links and degree of freedom (DOF), research progress in this area has been limited.

Few researchers contributed to modelling a biped robot in Matlab/SimMechanics environment. A SimMechanics model represents physical model through blocks and converts it into time efficient mathematical model [4] . Mester-G [7] applied the Euler-Lagrange method for dynamic modelling of a 20 D.O.F(Degree of freedom) underactuated biped robot and verified his results by Robotics toolbox of Matlab/SimMechanics. Marlon Fernando Velsquez-Lobo et al [13] presented

a methodology for modelling of a 5 link biped robot, which is connected through revolute joints, in Matlab-SimMechanics. They have modelled ground contact as well. Mathworks Student development team [12] developed a SimScape model of walking robot implementing genetic algorithm to find optimal trajectory for walking.
The main objective of this project is to make a model of a biped robot and simulate it in MATLAB/Simulink and improve its dynamic stability changing controller parameters. The model has seven links and six revolute joints. Finally, Proportional-integral-derivative (PID) control on ankle joint is applied.

2 Modelling of System in Matlab/SimMechanics

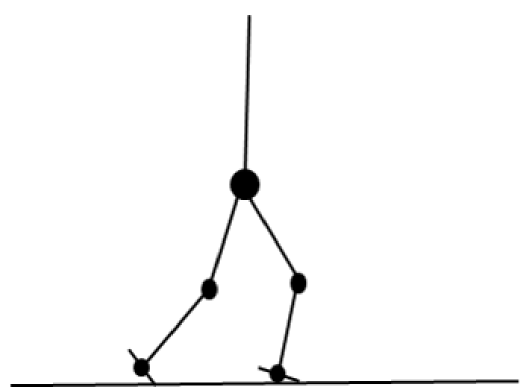

Fig. 1. Kinematic structure of the biped robot

Fig. 1 shows kinematic structure of 6 D.O.F biped robot to be modelled. Different approaches for biped locomotion control existing in the literature are Zero moment point (ZMP) detection, [11] Passive walking method [6] and Walking primitive [2]. Walking primitive approach is followed for our biped locomotion in Matlab/SimMechanics. In this approach positions for all joints are set in prior and required torque for motion is calculated at each step.Biped robot is modelled using SimMechanics which accepts its system as a combination of block diagrams and performs dynamic simulation using the standard Newtonian dynamics of forces and torques.The model will have foot, lower leg, and upper leg and torso/trunk blocks. The foot is connected with the lower leg through a rotary joint. Lower and upper legs are connected via knee joint and hip joint connects the upper leg with the torso. Therefore, one leg is having three joints and four links (torso is common to both the legs). Torso, leg, foot are modelled specifying geometric parameters and ground contact is modelled using Sphere to plane force block of SimMechanics [8] from Matlab contact library.

2.1 Torso modelling

Torso is modelled as a rectangular block connected from right to left hip.Representation of torso in SimMechanics environment is shown in Fig. 2. Dimensions of the torso are represented in Table 1

Table 1. Torso Parameters

Torso Parameter	Value
Length	10 cm
Breadth	8 cm
Width	5 cm
Density	950kg/m^3

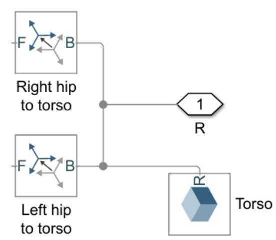

Fig. 2. SimMechanics block diagram for torso

2.2 Leg modelling

Legs are modelled as rigid cylinders. Each leg contains three links named as foot, lower leg and upper leg(Simulink block diagram is shown in Fig. 3). They are connected by revolute joints which are named as ankle joint (between foot and lower leg), knee joint (between the lower leg and upper leg) and hip joint (between upper leg and torso). All joints are actuated by input motions.Required parameters for legs are represented in Table 2.

Table 2. Leg Parameters

Leg Parameter	Value
Leg radius	.75 cm
Lower leg length	10 cm
Upper leg length	10 cm

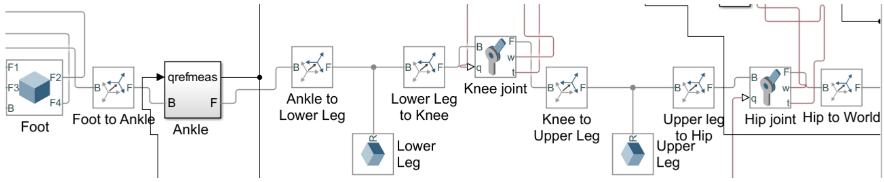

Fig. 3. SimMechanics block diagram for leg

2.3 PID control modelling

Proportional-Integral-derivative controls are applied at ankle joints of each leg(block diagram of it is shown in Fig. 4). An initial torque is applied at ankle joint by motor. The difference between the reference and actual angular position of ankle joint is taken as input to the PID controller which actuates necessary torques to that joint.

Parameters of PID controller as found after PID tuning are given as K_p (proportional gain) =0.1, K_i (Integral gain)=0.57,K_d (differential gain)=0.1

Equation for calculating actuation torque at ankle is given in equation 1

$$\tau = K_p(q - q_r) + K_d \frac{d(q - q_r)}{dt} + K_i \int (q - q_r)dt \tag{1}$$

Here q is the actual ankle joint angle after application of torque whereas q_r is

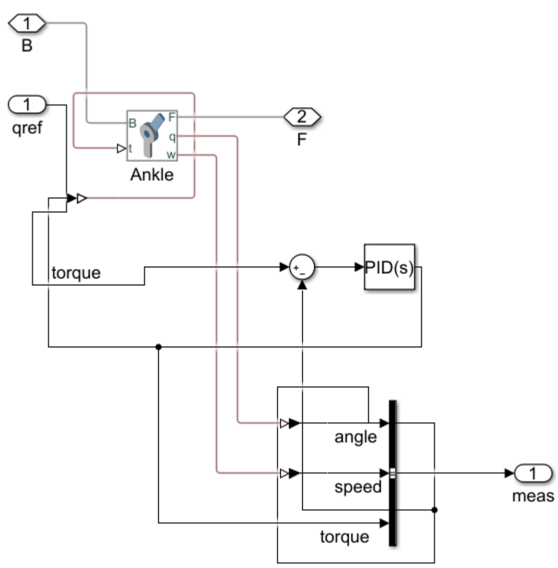

Fig. 4. SimMechanics block diagram for PID control at ankle

the reference ankle joint angle

2.4 Ground contact modelling

Contact force between foot and ground is unilateral i.e. only repulsive force exists between them when they come to contact. To model this kind of contact, Sphere to plane force [8] SimMechanics block has been used. This block implements a contact force between a sphere and a plane. Feet are placed at the spherical end and the ground is at the plane end.Block diagram of ground contact in SimMechanics environment is shown in Fig. 5. All parameters of ground contact are represented in Table 3.

Table 3. Ground contact Parameters

Ground contact parameter	**Value**
Contact stiffness	2500N-m/deg
Contact damping	100N-m/deg/s
Ground static friction coefficient	0.6
Ground kinematic friction coefficient	0.8
Ground plane width	3m
Ground plane height	0.025m
Ground plane length	25m

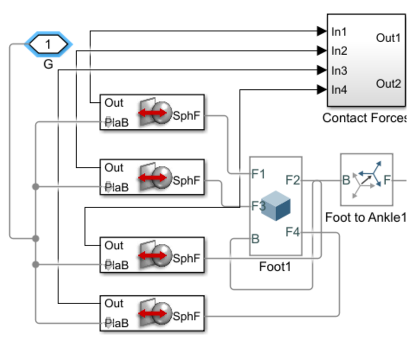

Fig. 5. SimMechanics block diagram for Ground contact

3 Simulation and Results

Input gait is provided in the form of joint trajectories .In a walking cycle, All six joint trajectories(two ankle,two knee and two hip joints) are expressed as cubic polynomials of time. A cubic polynomial requires 4 points at 4 given time instants to specify all coefficients. To make joint trajectories position, velocity and acceleration continuous,additional 3 conditions are required. To take that into consideration 3 more joint angles at 3 given time instants are specified . So 7 joint angles have been specified at given time instants for generating trajectory for each joint.

All simulations are based on the ODE 15s solver which is used for solving stiff problems i.e. problems in which two or more solution components vary on drastically different time scales [4]. Performance of PID controller also depends on the selection of controller gains. Initially, simulation was performed with default gains K_p(proportional gain) =1, K_i(Integral gain)=0 and K_d (differential gain)=2(to maintain condition for critical damping). Later on, auto-tuning was applied with the help of Transfer function based PID tuner app available in SimMechanics and optimal PID controller gains are noted asK_p(proportional gain) =0.05, K_i(Integral gain)=0.57 and K_d (differential gain)=0.05. Simulations results of walking due to given trajectories and applied PID control at ankles are shown below. Bipedal motion achieved with the these control parameters show that robot walking is continuous, smooth and dynamically stable i.e. it does not fall off during locomotion. It is observed that increasing K_p and K_d and reducing K_i from optimal values make biped walking non human like gait,unstable.Details about dynamic stability is discussed in 4

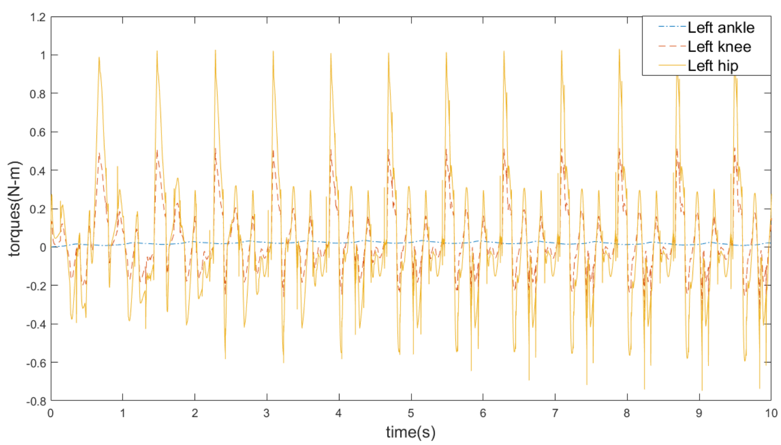

Fig. 6. Plot of torques at joints at left leg

Fig. 6 shows that required torque at ankle joint is maximum when it leaves the ground (changes from support phase to swing phase). Otherwise, torque requirement at the hip joint is greater compared to the other joints.It can be validated from the fact that in a serial chain system revolute joint that connects fixed base and 1st link requires more torque than others as 1st joint needs to

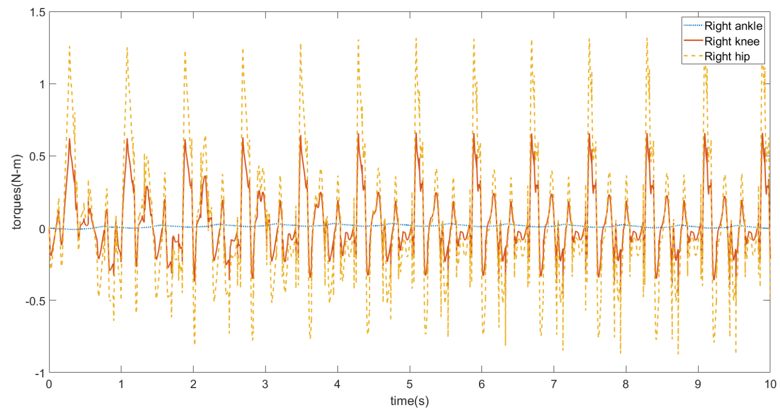

Fig. 7. Plot of torques at joints at right leg

move the whole system. Here hip joint is serving the same purpose.Torque profile is similar in right leg and left leg as shown in Fig. 6 and Fig. 7.

Angular speeds of three joints (ankle, knee and hip) for both the legs are presented in Fig. 8 and Fig. 9.

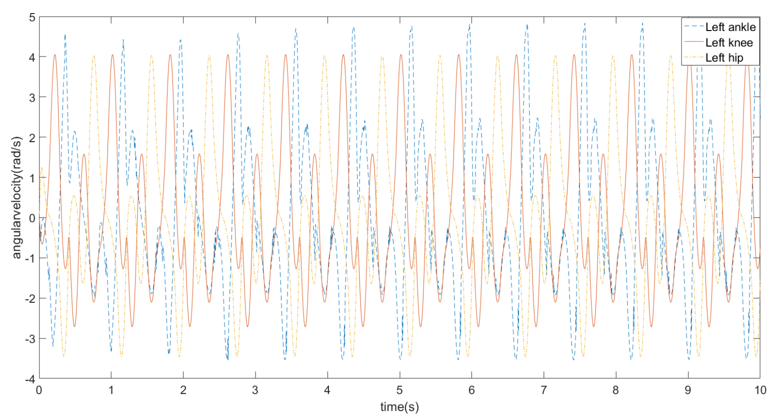

Fig. 8. Angular velocity at three joints at left leg

Maximum speed is seen for ankles and knee and hip joints are moving in similar manner. Maximum speed of all the joints are not seen at the same time and maximum torque is seen for hip joint when it moves with maximum hip speed. The 3-D model of the robot during simulation is shown in Fig. 10.

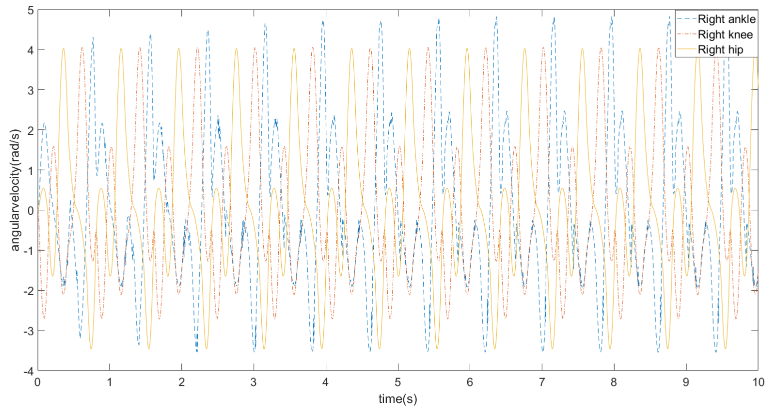

Fig. 9. Angular velocity at three joints at right leg

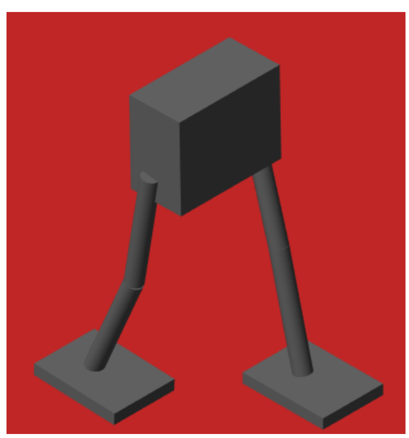

Fig. 10. Biped Robot model in SimMechanics environment

4 Dynamic stability

There are few methodologies for available in literature for analysing stability for a biped robot model . Most used approaches are based on zero moment point(ZMP)[11] , limit cycle theory [9] , Lyapunov theory [3]. In this paper limit cycle theory is used to check and improve dynamic stability of the biped model.

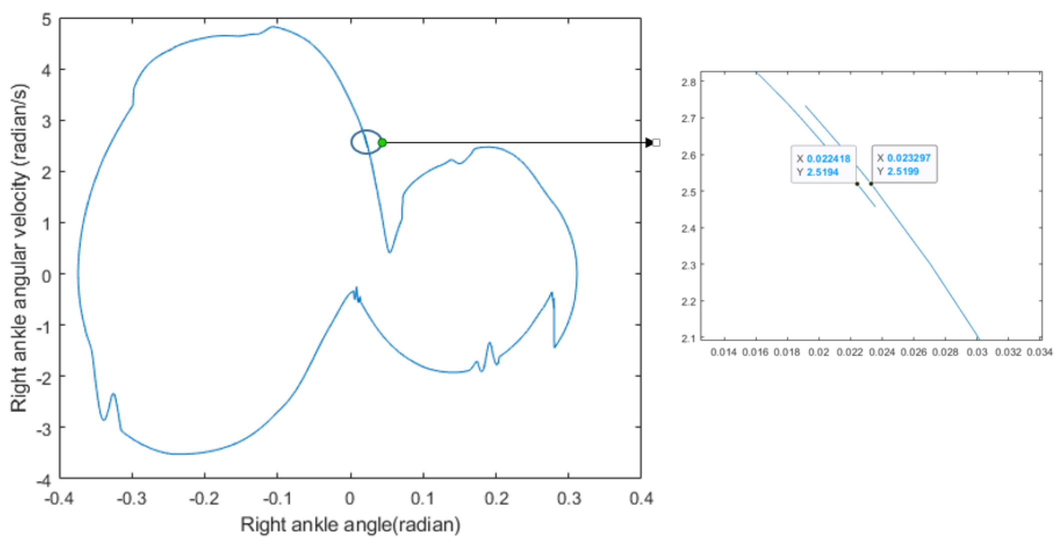

Fig. 11. phase portrait for right ankle at optimal condition

For a biped locomotion to be stable, phase portrait of controlled variable should conform to a limit cycle as walking progresses[9]. In biped robot system which is discussed in this paper, PID controllers are applied at right ankle and left ankle only. So phase portrait of associated joint angles and angular velocities for last two walking cycles are studied and presented in Fig. 11 and Fig. 12. If K_p and K_d are improved further, distance between last 2 walking cycles increase.

In Fig. 12 controller parameters used are K_p(proportional gain) =1, K_i(Integral gain)=0 and K_d (differential gain)=2. In Fig. 11 distance between last two walking cycle is lesser than that in Fig. 12. Varying K_p ,K_i and K_d it can be stated that distance between last two walking cycle is minimum for optimal controller gains as mentioned in 2.3. It refers to the fact that with optimal controller gain values ,biped robot is dynamically most stable .

It is also observed that there are two areas in Fig. 12 where significant angular velocity is changed with small change in angular displacement. This phenomenon is observed at the time of impact on ground with a high velocity. For walking of

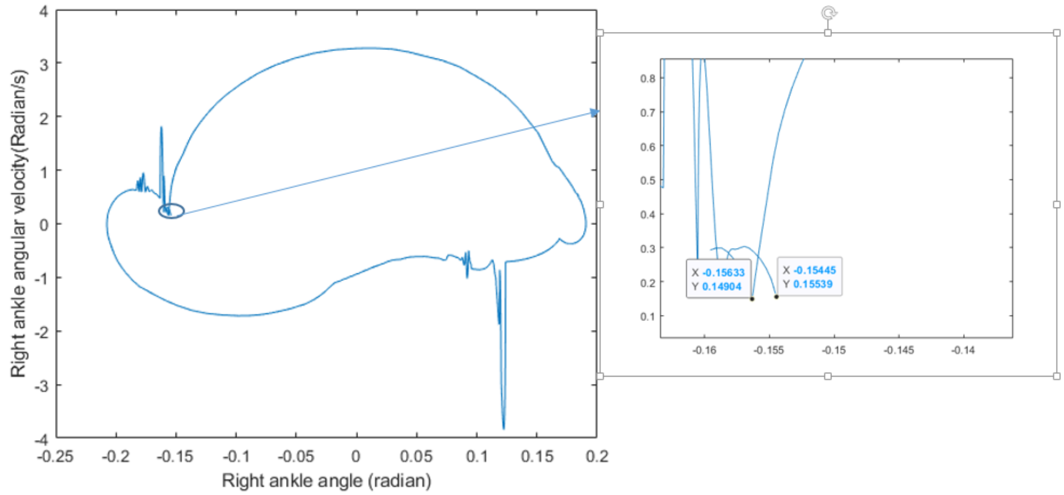

Fig. 12. phase portrait for right ankle at non optimal condition

a robot this may damage the system . So this kind of situation should be avoided as well.

5 Conclusion

This paper presented a way to model 6 DOF biped robot system in Matlab/SimMechanics. Simulation with and without PID tuning parameters makes noticeable difference in walking pattern and dynamic stability of the system. With PID-tuned controller, movement of each joint occurs in more organized way and more human like movement is obtained. A limitation of this system is that it produces flat feet motion. To overcome this problem toe joints can be implemented at each foot. In turn it will incorporate more complexity to the system as more controllers will be required and simulation of the system will require more time as degree of freedom of the system will increase. Walking of model can be made more humanoid if contact forces are fed as feedback to movement of the system.

References

1. Bouyarmane, K., Vaillant, J., Keith, F., Kheddar, A.: Exploring humanoid robots locomotion capabilities in virtual disaster response scenarios. In: 2012 12th IEEE-RAS International Conference on Humanoid Robots (Humanoids 2012). pp. 337–342. IEEE (2012)
2. Denk, J., Schmidt, G.: Synthesis of walking primitive databases for biped robots in 3d-environments. In: 2003 IEEE International Conference on Robotics and Automation (Cat. No. 03CH37422). vol. 1, pp. 1343–1349. IEEE (2003)

3. Galloway, K., Sreenath, K., Ames, A.D., Grizzle, J.W.: Torque saturation in bipedal robotic walking through control lyapunov function-based quadratic programs. IEEE Access **3**, 323–332 (2015)
4. Inc., T.M.: https://in.mathworks.com/help/matlab/release-notes-R2015a.html/, accessed April 9, 2019
5. Kuswadi, S., Jazidie, A., et al.: Reinforcement learning based of five legs robot for rescue operations. Academic Research International **1**(2), 6 (2011)
6. McGeer, T., et al.: Passive dynamic walking. I. J. Robotic Res. **9**(2), 62–82 (1990)
7. Mester, G.: Modelling of the humanoid robot motion. Ipsi Journal, Transactions on Advanced Research, TAR, New York, Frankfurt, Tokio, Belgrade **7**(1), 21–25 (2011)
8. Miller, S.: https://in.mathworks.com/matlabcentral/fileexchange/47417-simscape-multibody-contact-forces-library/, accessed April 9, 2019
9. Ono, K., Takahashi, R., Shimada, T.: Self-excited walking of a biped mechanism. The International Journal of Robotics Research **20**(12), 953–966 (2001)
10. Sinnet, R.W., Zhao, H., Ames, A.D.: Simulating prosthetic devices with human-inspired hybrid control. In: 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems. pp. 1723–1730. IEEE (2011)
11. Takanishi, A., Naito, G., Ishida, M., Kato, I.: Realization of plane walking by the biped walking robot wl-10r. In: Theory and Practice of Robots and Manipulators, pp. 383–393. Springer (1985)
12. Team, M.S.C.: https://in.mathworks.com/matlabcentral/fileexchange/64227-matlab-and-simulink-robotics-arena-walking-robot/, accessed April 9, 2019
13. Velásquez-Lobo, M.F., Ramirez-Cortés, J.M., de Jesus Rangel-Magdaleno, J., Vázquez-González, J.L.: Modeling a biped robot on matlab/simmechanics. In: CONIELECOMP 2013, 23rd International Conference on Electronics, Communications and Computing. pp. 203–206. IEEE (2013)