Qualitative validation of humanoid robot models through balance recovery side-stepping experiments

Citation for published version (APA):

Assman, T. M., Zutven, van, P. W. M., & Nijmeijer, H. (2013). Qualitative validation of humanoid robot models through balance recovery side-stepping experiments. In *IEEE International Conference on Robotics and Automation (ICRA 2013), May 6-10, 2013, Karlsruhe, Germany* (pp. 4773-4778). Institute of Electrical and Electronics Engineers. <https://doi.org/10.1109/ICRA.2013.6631257>

DOI:

[10.1109/ICRA.2013.6631257](https://doi.org/10.1109/ICRA.2013.6631257)

Document status and date:

Published: 01/01/2013

Document Version:

Author's version before peer-review

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Qualitative validation of humanoid robot models by side-stepping experiments

Tim Assman, Pieter van Zutven and Henk Nijmeijer

Dynamics and Control Group, Department of Mechanical Engineering, Eindhoven University of Technology
P.O. Box 513, 5600 MB, Eindhoven, the Netherlands

Email: t.m.assman@student.tue.nl, p.w.m.v.zutven@tue.nl, h.nijmeijer@tue.nl

Abstract—Simple models like a linear inverted pendulum are frequently used in literature to approximate the complex dynamics of a humanoid robot. These models neglect the influence of feet, discontinuous ground impact, internal dynamics and coupling between the 3D coronal and sagittal plane dynamics. In general extensive multi-body models are more accurate and take these aspects into account, but give less analytical insight at a higher computational cost. The required model accuracy depends on the purpose of the model, but in literature, experimental validation of most models is lacking. Therefore, our goal is to show to what extent existing models describe the real dynamics of a humanoid robot. Our first contribution is the experimental evaluation of assumptions from simple models. Secondly, we qualitatively validate a 3D full multi-body model of our humanoid robot TULip by side-stepping experiments. Finally, we contribute an implementation of the multi-body model in the ROS Gazebo simulator.

I. INTRODUCTION

Robots ideally should be humanoid and bipedal to operate in environments that are designed for humans. Models can be created that approximate the complex dynamics of such robots. Models can be used on-line in control algorithms on the robot, for example to determine foot placement to prevent a fall. Or models can be used off-line to simulate the robot, and safely test control strategies before they are executed on the real robot. Several humanoid robot models with strongly varying properties and assumptions are available in literature.

Kajita et al. [1] state that a humanoid robot can be approximated by the Linear Inverted Pendulum Model (LIPM) depicted in Fig. 1a. The LIPM assumes a point foot and a single point mass, that is kept at constant height by the extension of a telescoping leg. Koolen et al. [2] use the LIPM to compute the step location in their Capture Point (CP) method. They show how the LIPM's stance leg can be extended by a foot to allow the use of ankle torques. Interaction between the swing foot and the ground at impact is, however, not considered. Kudoh et al. [3] approximate a human that is recovering balance by an inverted pendulum model with a rotational spring in the ankle, and a linear spring in the leg that absorbs part of the impact.

Hofmann's [4] inverted pendulum model is kept only at constant height after ground impact, to approximate the corresponding energy loss. Stephens [5] uses this model to compute the step location. The model in the Foot Placement Estimator (FPE) method by Wight [6] has constant leg

Fig. 1. Models approximating a humanoid robot.

length, includes inertia, and computes impact using conservation of angular momentum (Fig. 1b).

The previous models assume all the masses of the robot can be approximated by a single mass at the robot's Center of Mass (CoM) position. The multi-body model by Zutven et al. [7] consists of an arbitrary number of masses and moments of inertia to determine the Foot Placement Indicator (FPI). An example is shown in Fig. 1c. Cho et al. [8] use a model with three masses and extendable legs to determine foot placement for a hopping robot, and even consider a flight phase.

All the previously mentioned models describe the dynamics only in 2D. To describe the dynamics of the robot in 3D, often two separate 2D models are evaluated in the coronal and sagittal plane, neglecting coupling between these planes [1], [2]. In general, 3D full multi-body models are more accurate and take the above aspects into account, but give less analytical insight at a higher computational cost.

The required model accuracy depends on the purpose of the model, but in literature, experimental validation of humanoid robot models is lacking. Therefore, the goal of this paper is to show to what extent commonly used models accurately describe the dynamics of our humanoid robot TULip [9]. The first contribution of this paper is the experimental evaluation of the, in our view, most important assumptions in commonly used models. In Section II, we investigate the influence of different aspects on the overall system dynamics in stepping experiments on our humanoid robot TULip. We consider the influence of the feet, discontinuous ground impact, internal dynamics and coupling between the dynamics in the coronal and sagittal plane. The second contribution is the experimental validation of a 3D full multi-body model of TULip, described in Section III. Finally, we

Fig. 2. The humanoid robot TULip.

contribute an implementation of the multi-body model in the ROS Gazebo simulator. A video of the experiments and simulations is provided with this paper.

II. SIDE-STEPPING EXPERIMENTS

In the previous section, four main simplifications in models from literature are identified: the robot is approximated with point feet and a single mass, discontinuous ground impact is neglected, and coupling between dynamics in the coronal and sagittal plane is neglected. Our humanoid robot TULip is used in two side-stepping experiments to investigate the real dynamics and evaluate these assumptions.

A. The humanoid robot TULip

The setup that we use to validate the model assumptions is the anthropomorphic humanoid robot TULip. TULip, as depicted in Fig. 2a, is position controlled, 134[cm] tall and 23[kg] heavy. Three revolute joints around the x-, y-, and z-axis are placed in each hip, one around the y-axis in each knee and two around the x- and y-axis in both ankles as schematically depicted in Fig. 2b. DC motors drive these joints through gearboxes and a cable transmission. On each joint axis a Scancon incremental encoder measures the joint angle. An XSens Inertial Measurement Unit (IMU) on TULip's right shoulder measures acceleration, angular velocity and earth-magnetic field to reconstruct its 3D orientation. At four points below the corners of each foot, Tekscan Flexiforce sensors measure the ground contact force. Besides research in the field of bipedal walking, TULip is used to participate in the adult size humanoid soccer league of RoboCup within the team Tech United [10], [11].

B. Experimental setup

Two simple experiments are chosen that focus on the evaluation of the model assumptions from literature. The control scheme is kept as simple as possible to minimize its influence on the dynamics. Similar to the initial state of the models in Fig. 1, the robot rotates on one straight leg until the other straight leg hits the ground. The robot steps sideward instead of forward, because then the feet and CoM rotate

Fig. 3. Snapshots and visualizations from the experiment where the robot rotates to its left in a static posture. The colored lines at the corners of the feet show the contact force at that location.

in the same plane and better imitate a 2D model. Although the experiments are simple, they still include many dynamic aspects that allow in-depth analysis of model assumptions.

In the first experiment, all joints are kept at the initial configuration of the robot, shown in the top row of Fig. 3. The desired joint angle of right hip roll (x) is set equal to $-0.3[\text{rad}]$ and the left hip roll (x) is set equal to $0.3[\text{rad}]$. The desired joint angles of the other joints are set equal to zero. The robot's head is removed to protect it from damage. In order to create unactuated 'passive' joints and imitate point feet in the stepping direction, the ankle roll (x) gains are set equal to zero. Then the robot is released.

In the second experiment (top row of Fig. 7), the left leg is rotated during the experiment to investigate the influence of the mass in the legs on the internal dynamics. The robot starts standing on its right leg, with an initial right hip roll (x) angle of $-0.4[\text{rad}]$ and right ankle roll (x) angle of $-0.08[\text{rad}]$ tuned to make it stand stable without needing additional support. The left hip roll (x) joint is then suddenly rotated from $0[\text{rad}]$ to $0.3[\text{rad}]$ in $0.5[\text{s}]$.

C. Evaluation of the model assumptions

The bottom rows of Fig. 3 and Fig. 7 show a visualization of the robot's legs reconstructed from the sensor data defined in the right-handed world coordinate frame. The length of the colored lines originating from the corners of each foot are proportional to the force sensor data at the same location. There is a colored coordinate frame fixed between the hips, and its orientation is determined based on the IMU data. The purple arrow originating from this frame is proportional to, and in the direction of the resultant acceleration. The experiments are shown in the video accompanying this paper.

The measurements of the joint encoders and the torso orientation from the IMU for the first experiment are also shown in graphs in Fig. 4, and for the foot force sensors in Fig. 5a. The measurement data of the second experiment with moving leg is shown in Fig. 6. We repeated the experiments three times, and no significant differences between the subsequent trials were observed. In this section only the experiments are

Fig. 4. The robot rotates around its ankle roll (x) joints that imitate point feet. But the ankle joints never reach zero again, which indicates energy loss due to impact. The oscillation of the roll (x) orientation of the torso has a two times lower frequency in the simulation compared to the experiment. In the experiment the robot also rotates around its ankle pitch (y) joints because of the influence of the toes and heels, resulting in a pitch (y) oscillation perpendicular to the stepping direction.

considered, in Section III the simulation data in the graphs will be discussed. The measurements are used to evaluate the most important model assumptions from literature:

1) *Impact*: The robot starts in an upright orientation on its right leg (Fig. 3.t1), with right ankle roll (x) angle equal to zero (Fig. 4a). The robot rotates to its left side, and potential energy is converted into kinetic energy. When no energy would be lost at impact, the robot's motion would be symmetric around the double stance phase of Fig. 3.t3. All kinetic energy would be converted back into potential energy, and the robot would also reach an upright orientation on its left leg. But we do not see this in the experiment in Fig. 3.t4. After the left foot has adapted its orientation to the ground, the left ankle roll angle (x) remains far from zero (Fig. 4b). The only explanation for this behavior is that energy loss due to impact dynamics is significant. We expect that energy loss due to joint friction and damping is negligible.

Fig. 5a shows that instead of a single impact, multiple successive impacts occur during a single stance phase. This is caused by the coefficient of restitution of the rubber knobs at the corners of the feet, in combination with the considerably rigid posture of the robot. The sinusoidal shape at the end

(a) Experiment. Multiple impacts are visible during a single stance phase. At the end the sinusoidal shape indicates that pressure is also exchanged while both feet remain in contact with the ground.

(b) Simulation. At the beginning of each stance phase, high impact forces are visible.

Fig. 5. Vertical force on corners of the feet are not equally distributed.

of Fig. 5a shows that exchange of foot pressure between the left and right foot continues while they remain in contact with the ground. The foot sensors saturate at 120[N].

2) *Point foot*: The joint friction and damping are low enough to successfully imitate a point-foot in the stepping direction by setting the ankle roll (x) gains equal to zero. This results in a smooth oscillation of the roll (x) orientation in Fig. 4c. The measured oscillation is not around zero, because the IMU has difficulties to distinguish the accelerations due to gravity from the accelerations due to impact. This leads to an incorrect vertical z-axis, and a temporary negative offset to the roll (x) angle that is defined relative to this axis. We conclude that robots without ankle actuation can accurately be approximated by point footed models.

3) *3D dynamics*: Due to calibration, the robot initially leans slightly forward when the right ankle pitch (y) angle is zero. The ankle pitch (y) gains are needed to balance the robot perpendicular to the stepping direction. However, the ankle pitch (y) joints can easily rotate through the backlash, causing the chattering behavior visible in Fig. 4d-e. Due to an asymmetric mass distribution, the robot initially rotates backward around the right ankle pitch (y) joint (Fig. 4d). When the left foot lands inclined on the ground at impact (Fig. 4e), the robot rotates further backward (Fig. 4f).

Fig. 6. When the leg is quickly rotated, the action of the swing leg has an equal opposite reaction on the rest of the body (arrows). While the leg accelerates upward, the torso starts to rotate in the forward direction towards the leg around its right hip. The robot pushes the leg mass to the robot's left side, and as a reaction the rest of the robot's body is pushed to its right side. Therefore the robot rotates around its right ankle roll (x) joint. For an instant the foot pressure shifts to the outer side of the foot.

The joint controller compensates for the resulting error and straightens the ankle. This makes the robot rotate forward, and the robot's inertia causes the right ankle pitch (y) to overshoot zero, creating a new error. This effect results in a harmonic damped pitch (y) oscillation in Fig. 4f before the robot eventually comes to rest. An explanation is that the dynamics in the stepping direction is non-negligibly coupled with the dynamics perpendicular to the stepping direction.

4) *Single mass*: Most models approximate the multiple masses of a robot by a single mass at its CoM position. When the masses are not separately taken into account, their internal dynamics is neglected. But when for example two legs of the robot move in opposite direction, it may influence the overall dynamics of the robot while the CoM position and velocity do not change. We investigate the influence of the leg mass on the internal dynamics of the robot.

In the second experiment, the robot quickly rotates its left hip roll (x) joint, as shown in Fig. 6a. The acceleration and deceleration of the leg have an opposite effect on the rest of the robot. At the start of the leg rotation, the robot accelerates the leg by applying a hip torque, indicated by the rotational red arrow in Fig. 7.t2. By Newton's third law, the mass and inertia of the leg apply an equal opposite torque to the rest

Fig. 7. The robot's left leg is quickly rotated upward (red arrows), and this has an opposite effect on the rest of the robot (blue arrows).

of the body, shown by the blue rotational arrow in the same figure. This makes the torso rotate in the direction of the blue rotational arrow, towards the robot's left side around the right hip roll (x) joint. This is indicated by the left arrow in Fig. 6b and Fig. 6d.

At the same time this hip torque creates an outward force, in the direction indicated by the straight red arrow in Fig. 7.t2. As a reaction, the mass and inertia of the leg apply an equal opposite force on the robot, indicated by the straight blue arrow in Fig. 7.t2. This force pushes the robot into the negative y-direction, and results in a rotation around the robot's right ankle roll (x) joint (Fig. 6c). The ankle joint controller tries to keep the right ankle roll (x) angle zero by applying a torque on the foot. Therefore the outer side of the robot's right foot is pushed harder against the ground. In the experiment, a decrease at the inner heel is visible in Fig. 6f. At the deceleration phase, the exact opposite effects happen as indicated with the arrows in Fig. 7.t4 and the right arrows in Fig. 6. We can conclude from these observations that a single mass model may not sufficiently describe the full dynamics of a humanoid robot.

III. MULTI-BODY SIMULATION

A. Multi-body model

With the previous experiments, it is shown that simple models do not describe all dynamics of a sideward step. We identified that energy loss due to impact and influence of a moving leg mass on the internal dynamics are important. Also finite-sized feet cause an oscillation perpendicular to the stepping direction. In this section, we contribute and experimentally validate an extensive multi-body model that includes these aspects and more accurately describes the experiments. The humanoid robot Tulip is modeled as a 3D multi-body model, where all joints and links are taken into account as shown in Fig. 2b. Additionally, after each ankle pitch joint, an unactuated joint with low damping and joint limits of $\pm 1[\text{deg}]$ models backlash. Model parameters are estimated through identification experiments [12].

Fig. 8. The accuracy and repeatability of the ground constraint forces improves for more iterations. The sum of ground forces is very close to the force that would be expected from the weight of the robot.

B. Gazebo simulator

A fast and accurate dynamic simulator is needed to quickly and safely test control algorithms for humanoid robots, like push recovery strategies. Therefore the Gazebo simulator is chosen [13], which is integrated in the Robot Operating System (ROS). Equivalent data are retrieved from the simulation as are measured by the joint encoders, IMU and foot sensors on the robot. The existing motion controller that runs on TULip can also communicate with the simulator using shared memory. The Gazebo simulator uses the Open Dynamics Engine (ODE), that integrates the Newton-Euler equations of motion with fixed step size, and solves them with projected Gauss-Seidel with successive over-relaxation [14]. A ROS package with the simulation model will become available on-line at our website [10].

C. Validation of the contact model during standing

The robot is simulated standing on the ground in an upright posture as shown in Fig. 2c. Contact constraints try to prevent the knobs at the corners of each foot from penetrating through the ground. Using Gazebo's default simulation settings 10 solution iterations are done at each time step of $0.001[s]$. This number of iterations is not sufficient to obtain accurate results that satisfy all constraints. The corrections that are being made to reduce these constraint errors result in jittering ground contact forces, shown in Fig.

Fig. 9. Snapshots and visualizations from the simulation where the robot rotates to its left in a static posture.

Fig. 10. The simulation where the robot's left leg is quickly rotated upward.

8a. By default ODE iterates the constraints in a random order to improve convergence (consult `quickstep.cpp` [15] for more information). This makes the simulator also non-deterministic for a small number of iterations, see the difference when the same simulation is repeated in Fig. 8a. Increasing iterations strongly reduces jittering in the contact forces up to an acceptable level of $0.3[N]$. It also gives exactly the same results when the simulation is repeated (Fig. 8d). For 10 iterations, the height of the simulated IMU is slowly oscillating with an amplitude of $0.2[mm]$ (Fig. 8f). When increasing the iterations from 10 to 100, the simulated IMU position is increased by $5[mm]$ and the oscillations are not present anymore. The total sum of ground contact forces only differs $0.2[N]$ from the force that is expected from the weight of the robot (Fig. 8e). The simulation is realtime for 10 iterations, but has a realtime factor of 0.05 for 3000 iterations. If this is too slow, the user can conveniently make a trade-off between speed and accuracy by setting the number of iterations.

D. Qualitative validation of the multi-body model

The sidestepping experiment with static posture and moving leg are imitated in the simulator. The results are shown in

graphs in Fig. 4, 5b and 6, and the simulations are displayed in Fig. 9, 10, and in the video accompanying this paper.

Overall the simulator accurately describes the experiments, and it includes the main aspects previously discussed. The energy loss due to impact is modeled, as the robot does not reach an upright position in Fig. 9. The feet can behave as a point contact in the stepping direction as shown in Fig. 4a. The simulation describes the oscillation perpendicular to the stepping direction in Fig. 4f, because the model includes ankle pitch (y) backlash and has feet. The effects that are caused by the moving leg mass on the rest of the robot in the simulation are qualitatively the same as in the experiments. The increase and decrease of the contact forces as indicated by the arrows in Fig. 6 is similar.

There are also some differences. The most important one is that the simulation's roll (x) oscillation has a two times lower frequency compared to the experiment. Backlash of joints other than the ankle pitch (y) joints is not modeled in the simulation and could be responsible. The model parameters were earlier estimated in identification experiments [12], but a small difference in mass distribution can already have a significant influence on the dynamics. Gazebo uses only a simple linear friction model, and after tuning the joint damping parameters, there remain differences between e.g. ankle roll (x) angle evolutions in Fig. 4a-b. It is also likely that there is a big difference in energy loss at impact.

Ground contact in simulation is different from the experiment in Fig. 5. In simulation, ground contact is strongly dependent on factors such as the Gazebo constraint force parameters, the coefficient of restitution and the contact model, and therefore hard to match the experiment. In the experiment, the foot sensors saturate, have a lower sampling rate and resolution, and there might be some inaccuracy in their calibration. Obviously, the ground reaction forces also differ when the motion of the robot is different.

IV. CONCLUSIONS AND RECOMMENDATIONS

The first contribution of this paper is the experimental evaluation of the, in our view, most important assumptions in commonly used models. Simple models from literature are useful for analysis and implementation in on-line control algorithms, but some model assumptions discard some important dynamic aspects that are present in stepping experiments of our humanoid robot TULip.

When the robot quickly rotates its swing leg, the action of the swing leg has an equal opposite reaction on the rest of the body. Therefore the leg mass influences the internal dynamics of the robot, which are neglected when the robot is approximated by a single mass. When the robot rotates from standing on one leg to the other leg, it does not reach the same height and corresponding potential energy. This is caused by discontinuous ground impact that is neglected in some models. Point feet are successfully imitated on TULip by setting the gains of the ankle joints in the stepping direction equal to zero. Already a slight initial CoM offset in combination with ankle pitch (y) backlash results in an oscillation perpendicular to the stepping direction, and

corresponding ankle gains are needed to balance the robot. The amplitude increases when the feet are not landing flat on the ground at impact. This shows coupling between the dynamics in the stepping direction and the dynamics perpendicular to the stepping direction.

The second contribution is the experimental validation of a 3D full multi-body model. Overall, the multi-body model accurately describes the experiments, and includes the main dynamic aspects. The most important difference is that the oscillation in the stepping direction has a two times lower frequency in simulation than in the experiment. This is probably caused by multiple factors including backlash that creates an initially higher velocity than the simulation, differences in CoM position, an inaccurate joint friction model, and differences in the impact model. Finally, a ROS package with the simulation model will become available on-line at our website [10].

REFERENCES

- [1] S. Kajita, F. Kanehiro, K. Kaneko, K. Yokoi, and H. Hirukawa, "The 3D linear inverted pendulum mode: a simple modeling for a biped walking pattern generation," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2001, pp. 239–246.
- [2] T. Koolen, T. de Boer, J. Rebula, A. Goswami, and J. Pratt, "Capturability-based analysis and control of legged locomotion, part 1: Theory and application to three simple gait models," *The International Journal of Robotics Research*, vol. 31, no. 9, pp. 1094–1113, 2012.
- [3] S. Kudoh, T. Komura, and K. Ikeuchi, "Stepping motion for a human-like character to maintain balance against large perturbations," in *IEEE International Conference on Robotics and Automation*, 2006, pp. 2661–2666.
- [4] S. Jo and A. Hofmann, "Bipedal walking from neurological and biomechanical principles," *Biological cybernetics research trends*, pp. 5–53, 2007.
- [5] B. Stephens, "Humanoid push recovery," in *7th IEEE-RAS International Conference on Humanoid Robots*, 2007, pp. 589–595.
- [6] D. Wight, E. Kubica, and D. Wang, "Introduction of the foot placement estimator: A dynamic measure of balance for bipedal robotics," *Journal of Computational and Nonlinear Dynamics*, vol. 3, pp. 1–10, 2008.
- [7] P. van Zutven, D. Kostic, and H. Nijmeijer, "Foot placement for planar bipeds with point feet," in *IEEE International Conference on Robotics and Automation*, 2012, pp. 983–988.
- [8] B. Cho, S. Park, and J. Oh, "Stabilization of a hopping humanoid robot for a push," in *10th IEEE-RAS International Conference on Humanoid Robots*, 2010, pp. 60–65.
- [9] D. Hobbelen, T. de Boer, and M. Wisse, "System overview of bipedal robots Flame and TULip: tailor-made for limit cycle walking," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2008, pp. 2486–2491.
- [10] Website of Tech United and the humanoid robot TULip. [Online]. Available: <http://www.techunited.nl/en/tulip/>
- [11] P. van Zutven, S. van Dalen, T. Assman, J. Caarls, C. Çilli, M. Aarts, T. Boshoven, P. Mironchyk, E. Ilhan, and H. Nijmeijer, "Tech United Eindhoven RoboCup adult size humanoid team description 2012." Robocup Symposium papers, 2012.
- [12] P. van Zutven, D. Kostić, and H. Nijmeijer, "Parameter identification of robotic systems with series elastic actuators," in *8th IFAC Symposium on Nonlinear Control Systems*, 2010, pp. 350–355.
- [13] E. Drumwright, J. Hsu, N. Koenig, and D. Shell, "Extending open dynamics engine for robotics simulation," *Simulation, Modeling, and Programming for Autonomous Robots*, pp. 38–50, 2010.
- [14] K. Erleben, "Velocity-based shock propagation for multi-body dynamics animation," *ACM Transactions on Graphics*, vol. 26, no. 2, pp. 1–20, 2007.
- [15] R. Smith. Open Dynamics Engine source code. [Online]. Available: <http://sourceforge.net/projects/opende/files/>