ICRA 2017, Singapore

Monday, May 29, 2017

2nd Full-Day Workshop on:

Robust Perception, Planning, and Control for Legged Robot Locomotion in Challenging Domains

Dimitrios Kanoulas, Ioannis Havoutis, Maurice Fallon, Andrea Del Prete, Eiichi Yoshida

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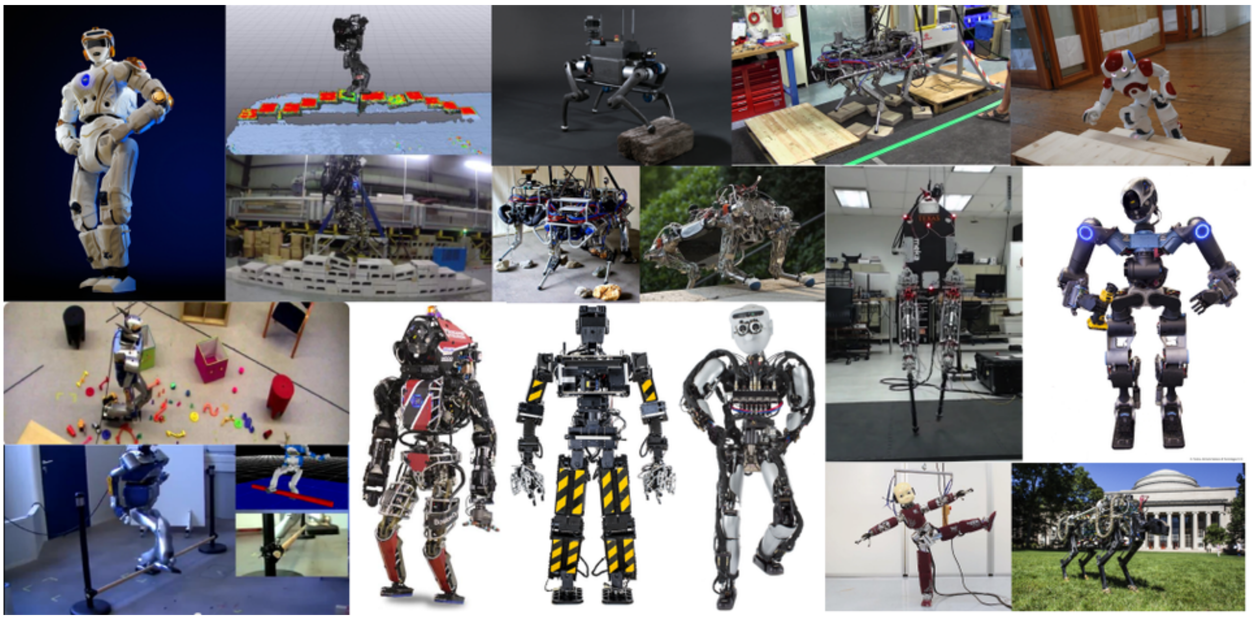
See: https://icra2017wslocomotion.wordpress.com/program

1. Introduction

1.1 Objectives



Recent advances in perception, planning, and control have enabled **legged robots** to successfully navigate in environments that are mostly known or well-structured and modeled. The DARPA Robotics Challenge (DRC) 2015 showed that in **real-world unstructured and uncertain environments** robots often lack robustness with regards to locomotion. From one side, this may be due to modeling uncertainties and actuation inaccuracies that affect the control loops. From the other side, both proprioceptive and exteroceptive perception and planning are crucial for detecting foothold and handhold affordances in the environment, and generating agile motions accordingly.

This workshop will provide a platform for researchers from **perception**, **planning**, and **control** in **legged robotics** to disseminate and exchange ideas, evaluating their advantages and drawbacks. This will include methods for robust control/planning optimization, such as Model Predictive Control, as well as path planning and perception methods for detecting footholds and handholds on challenging surfaces for legged robots including bipeds and quadrupeds. The goal is to show various ways from sensing the environment to finding contacts and planning/controlling the body and limb trajectories for achieving agile and robust locomotion. The aim is to foster collaboration among researchers that are working on legged robots to advance the state of the art in robot locomotion.

This full day workshop consists of a mixture of **presentations** on topics including sensing, perception, planning, motion generation, and control for various types of legged robots designed to work indoors and outdoors. To stimulate interaction, we also organize a **poster session** to encourage the participation of young researchers and promote discussion with the speakers and the audience. Moreover we allocate adequate time for questions and discussion to make the workshop as interactive as possible.

1.2 Topics of interest

- **<u>Control</u>**
    - robust model predictive control
    - robust optimization-based control
    - whole-body control
    - real-robot implementations
- **<u>Planning</u>**
    - probabilistic approaches to planning under uncertainty
    - locomotion and non-gaited locomotion planning
    - motion and path planning for high dimensional environments
    - contact planning and optimization
    - collision avoidance and self-collision avoidance
    - reactive behaviors and emergency behavior
- **<u>Perception</u>**
    - sensing for 3D reconstruction and scene modeling
    - proprioceptive and exteroceptive sensing fusion under uncertainty
    - localization and mapping for traversability in static or dynamic environments
    - environment segmentation and classification
    - visual learning for foot placement in rough terrain
    - feature extraction and semantic scene understanding and categorization

1.3 Support

This proposed workshop is supported by the **IEEE RAS Technical Committees** on:

1) Algorithms for Planning and Control of Robot Motion
[Fabrizio Flacco, Sertac Karaman, Hanna Kurniawati, Lydia Tapia]

2) Whole-Body Control
[Federico L. Moro, Luis Sentis, Jaeheung Park]

3) Model-Based Optimization for Robotics
[Katja Mombaur, Christopher G. Atkeson, Thomas Buschmann, Kensuke Harada, Abderrahmane Kheddar]

1.4 Acknowledgement

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1.5 Organizers

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2. Program

2.1 Program Schedule

08:30– 08:45 Welcome [Dr. Dimitrios Kanoulas]

Session 1 [Chair: Dr. Dimitrios Kanoulas]
08:45 – 09:10 Maurice Fallon — Univ. of Oxford, UK.
Title: "Multi-sensor Perception for Robust Localization of Humanoids and Quadrupeds"

09:10 – 09:35 Andrea Del Prete — LAAS-CNRS, France.
Title: "Robust Optimization and Motion Memory for Reliable Robotics"

09:35 – 10:00 Marco Hutter — ETH Zurich, Switzerland.
Title: *"Autonomous Legged Locomotion on Industrial Sites – ANYmal at the ARGOS competition"*

10:00 – 10:45 Coffee Break & Poster Session 1

Session 2 [Chair: Dr. Ioannis Havoutis]
10:45 – 11:10 Ludovic Righetti — MPI, Germany.
Title: "Towards more robust planning and control of contacts for locomotion"

11:10 – 11:35 Diego Pardo — ETH Zurich, Switzerland.
Title: "Motion planning and control of legged robots: Optimization-based approaches demonstrated on a real hydraulically actuated quadruped robot"

11:35 – 12:00 Francesco Nori — IIT, Italy.
Title: *"iCub Whole-Body Control Through Force Regulation with Distributed Tactile Sensing"*

12:00 – 13:30 Lunch Break

Session 3 [Chair: Prof. Maurice Fallon]
13:30 – 13:55 Taskin Padir — Northeastern Univ, USA .
Title: "Compositional Autonomy for Humanoid Robots"

13:55 – 14:20 Maren Bennewitz — University of Bonn, Germany.
Title: "Perception and Motion Planning for Humanoids in 3D Environments"

14:20 – 14:45 Alexander Stumpf — TU Darmstadt, Germany.

Title: "Towards Capable Open Source ROS-Frameworks for Real-Time Perception, World Modeling and Footstep Planning for Humanoid and Legged Robots"

14:45 – 15:30 Coffee Break & Poster Session 2

Session 4: [Chair: Dr. Andrea Del Prette]
15:30 – 15:55 Patrick Wensing — MIT, USA.
Title: "Real-time planning and control for the MIT Cheetah"

15:55 – 16:20 Evangelos Papadopoulos — NTUA, Greece.
Title: "Legged Robot Control Using Passive Dynamics and Active Compliance"

16:20 – 16:45 Luis Sentis — Univ. of Texas at Austin, USA.
Title: "Uncertainty in Human-Centered Robots"

16:45 – 17:00 Closing Remarks

2.1 Invited Speakers

Perception/Planning:

1. **Prof. Maurice Fallon** — University of Oxford, UK.
2. **Dr. Andrea Del Prete** — LAAS-CNRS, France.
3. **Prof. Marco Hutter** — ETH Zurich, Switzerland.
4. **Prof. Maren Bennewitz** — University of Bonn, Germany.
5. **Alexander Stumpf** — TU Darmstadt, Germany.
6. **Prof. Taskin Padir** — Northeastern Univ., USA.

Control/Planning:

1. **Dr. Ludovic Righetti** — MPI, Germany.
2. **Prof. Patrick Wensing** — MIT, USA.
3. **Dr. Diego Pardo** — ETH Zurich, Switzerland.
4. **Dr. Francesco Nori** — IIT, Italy.
5. **Prof. Evangelos Papadopoulos** — NTUA, Greece.
6. **Prof. Luis Sentis** — University of Texas at Austin, USA.

2.2 Poster Presentations

1. **N. Smit-Anseeuw, A. Nash, R. Vasudevan, and C. David Remy**
   Title: "Safe Online Learning Using Barrier Functions"
2. **A. Winkler and J. Buchli**
   Title: "Quadruped Motion Generation through Optimization"
3. **M. Khan, M. Ilyas**
   Title: "A Quadruped Robot made of a Bio Sourced Material"
4. **C. Mastalli, M. Focchi, I. Havoutis,A. Radulescu, D. Caldwell, C. Semini**
   Title: "Trajectory Optimization and Dynamic Walking Adaptation for Rough Terrain Locomotion"
5. **J. Machowinski, A. Boeckmann, S. Arnold, C. Hertzberg, S. Planthaber**
   Title: "Climbing Steep Inclines with a Six-Legged Robot using Locomotion Planning"
6. **A. Radulescu, I. Havoutis, D. Caldwell, C. Semini**
   Title: "Whole-body Trajectory Optimization for Non-periodic Dynamic Motions in Legged Systems"
7. **D. Kanoulas, A. Toumpa, C. Zhou, D. Caldwell, and N. Tsagarakis**
   Title: "Vision-Based Footstep Localization for Rough Terrain Locomotion"
8. ***A. Short and T. Bandyopadhyay***
   Title: "Legged Motion Planning in Complex 3D Environments"
9. **M. Wang, M.Wonsick, V. Dimitrov, X. Long, T. Padir,**
   Title: "In-situ Terrain Estimation and Stability Analysis for Bipedal Humanoid Robots"
10. **O. Urbann and I. Schwarz**
    Title: "An Alternative Derivation of the Linear Inverted Pendulum Model"
11. **S. Nobili, M. Camurri, C. Semini, and M. Fallon**
    Title: "Multi-sensor Perception for Robust Localization of Dynamic Robots"
12. **M. Camurri, M. Fallon, V. Barasuol, D. Caldwell, and C. Semini**
    Title: "State Estimation in the Loop for Accurate Base Pose and Velocity Tracking of Dynamic Legged Robots"
13. **M. Shafiee-Ashtiani, A. Yousefi-Koma, M. Shariat-Panahi, M. Khadiv**
    Title: "Robust bipedal Locomotion Control based on Model Predictive Control and Divergent Component of Motion"
14. **Y. Hu, K. Mombaur**
    Title: "Whole-body walking motion generation with optimal control"

3. Invited Speakers

3.1 Prof. Maurice Fallon - University of Oxford, UK.

Title: “Multi-sensor Perception for Robust Localization of Humanoids and Quadrupeds”

Abstract. In this talk I will present the development of state estimation, mapping and navigation algorithms for humanoid and quadruped robots. The first topic will overview the adaption of accurate registration methods to the Atlas and Valkyrie robots where explored the challenge of localisation over long baselines and with low point cloud overlap. Secondly we will explore how these methods can be fuse with Vision for a dynamic quadruped trotting and crawling in challenging lighting conditions. Finally I will present ongoing research in probabilistically fusing proprioceptive state estimation with dense visual mapping to allow a humanoid robot to build a rich dense map while overcoming dynamics, moving objects and challenging lighting conditions.

Bio. Maurice Fallon is a Departmental Lecturer at the University of Oxford. His research is focused on probabilistic methods for localization and mapping. He has also made research contributions to state estimation for legged robots and is interested in dynamic motion planning and control. Of particular concern is developing methods which are robust in the most challenging situations by leveraging sensor fusion. Dr. Fallon studied Electronic Engineering at University College Dublin and graduated in 2004. His PhD research was carried out in the Engineering Department of the University of Cambridge within the Signal Processing Group. Immediately after his PhD he moved to MIT. He worked as a post-doc and a research scientist in the Marine Robotics Group from 2008-2012. From 2012-2015 he was the perception lead of MIT’s team in the DARPA Robotics Challenge – a multi-year competition developing technologies for semi-autonomous humanoid exploration and manipulation in disaster situations. The MIT DRC team competed in several phases of the international competition, finishing 7th. From 2014, he was Lecturer at University of Edinburgh. There he led research in collaboration with NASA’s humanoid robotics program before moving to Oxford in April 2017.

3.2 Dr. Andrea Del Prete - LAAS-CNRS, France.

Title: "Robust Optimization and Motion Memory for Reliable Robotics"

Abstract. Optimal control provides an appealing theoretical framework to design, generate and control complex movements on any robotic system. However, the automatic generation of a trajectory from an optimal-control problem is often a costly mathematical process. As roboticists we then rely on two approximations to fasten the resolution. First, we accept sub-optimality; second, we design dedicated heuristics, such as simplified models (e.g. inverted pendulum), warm-start assumptions (e.g. motion graphs in computer animation), problem reformulation based on non-trivial properties (e.g. flatness in quadcopters). In the first part of this presentation, we will discuss the trade-off between these choices, and how we can imagine to go beyond them, by building offline a memory of motion from exhaustive sampling of the robot motion capabilities. The context of legged multi-contact locomotion will be used to emphasize the key aspects of the problem.

In the second part of this presentation we will focus on the problem of robustness. Nowadays legged robots are capable of performing locomotion and manipulation in semi-structured environments, but with a low level of reliability, which makes their application in real-world scenarios difficult, if not impossible. Simulated robots/avatars can instead easily and reliably perform dynamic movements such as human-like walking, running, jumping, kicking. What is preventing real robots from showing similar performance?

The difference between simulation and the real world can be explained through the countless uncertainties affecting these systems: the models of robot and environment are not accurate and the state estimation is delayed and noisy. Our idea is to account for uncertainties to improve robot performance and reliability. In particular, we recently addressed two different sources of uncertainties: joint-torque tracking errors and inertial parameter errors. We exploited robust optimization techniques (stochastic and worst-case) to try to guarantee the satisfaction of the robot constraints (i.e. force friction cones, joint bounds and balance constraints) despite the presence of these bounded uncertainties. Extensive results in simulation show the superiority of the proposed robust controllers, even in the presence of additional unmodeled uncertainties.

Bio. Andrea Del Prete was born in Cesena (Italy) in 1984. He received his degree in Computer Engineering (with honors) from the 2nd faculty of the University of Bologna (Italy) in 2009. In March 2013 he got his PhD from the Cognitive Humanoids laboratory of the department of

”Robotics Brain and Cognitive Sciences” in IIT, Genova. Since 2014 he has been a PostDoc at LAAS-CNRS in Toulouse, working on optimization-based control with HRP-2.

3.3 Prof. Marco Hutter - ETH Zurich, Switzerland.

Title: ”Autonomous Legged Locomotion on Industrial Sites – ANYmal at the ARGOS competition”

Abstract. In this talk, I will present our work with ANYmal at the ARGOS competition. I will provide an insight into different aspects on environment perception (obstacle detection and classification, localization, terrain mapping), navigation and maneuver planning. Moreover, I will briefly touch the aspect of locomotion control required to move around in such environment.

Bio. Marco Hutter is assistant professor for Robotic Systems at ETH Zurich and Branco Weiss Fellow. Marco is part of the national competence centers for robotics (NCCR robotics) and digital fabrication (NCCR dfab). His group is participating in several research projects, industrial collaborations, and international competitions (e.g. ARGOS challenge) that target the application of high-mobile autonomous vehicles in challenging environments such as for search and rescue, industrial inspection, or construction operation. Marco’s research interests are in the development of novel machines and actuation concepts together with the underlying control, planning, and optimization algorithms for locomotion and manipulation.

3.4 Dr. Ludovic Righetti - MPI, Germany.

Title: Towards more robust planning and control of contacts for locomotion

Abstract. Over the past few years there have been major progress for the control and planning of multi-contact legged locomotion. However, being able to create policies that are robust in face of uncertainties is still an important issue, especially when it comes to the contact situation. In this talk, I will give an overview of our research effort on the problem of optimal control of multi-contact. In particular, I will present our latest results on how the structure of multi-contact planning can be leveraged to create very efficient algorithms. Then I will discuss our recent results related to the importance of step timing adjustment to improve the robustness of walking. Finally I will discuss our current efforts in addressing robustness issues in a more systematic way.

Bio. Ludovic Righetti leads the Movement Generation and Control group at the Max-Planck Institute for Intelligent Systems (Tübingen, Germany) since September 2012. Before, he was a postdoctoral fellow at the Computational Learning and Motor Control Lab with Prof. Schaal (University of Southern California) between March 2009 and August 2012. He studied at the Ecole Polytechnique Fédérale de Lausanne (Switzerland) where he received an engineering diploma in Computer Science (eq. MSc) in 2004 and a Doctorate in Science in 2008 under the supervision of Prof. Ijspeert. He has received a few awards, most notably the 2010 Georges Giralt PhD Award given by the European Robotics Research Network (EURON) for the best robotics thesis in Europe, the 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) Best Paper Award and the 2016 IEEE Robotics and Automation Society Early Career Award. His research focuses on the planning and control of movements for autonomous robots, with a special emphasis on legged locomotion and manipulation.

3.5 Dr. Diego Pardo - ETH Zurich, Switzerland.

Title: “Motion planning and control of legged robots: Optimization-based approaches demonstrated on a real hydraulically actuated quadruped robot”

Abstract. The field of planning and control for legged robots has progressed extraordinarily over the last few years. Methods to make robots walk, run and jump exist and they are well understood. However, such methods are usually specific for a given task and robot morphology. Generalized methods are typically based on simplified models, and advanced robots are not using all their dynamic capabilities to move efficiently, but their motions are driven by the premise of ‘not to fall.’ The current challenge is to improve its performance (e.g., speed, versatility, robustness) and to find generic frameworks able to generate diverse types of dynamic motions from simple specifications.
In this talk, I will present the research conducted in the Agile and Dexterous Robotics Lab at ETH Zürich towards the motion planning and control of legged robots. We have addressed this problem using numerical optimization and learning approaches, and we have developed solutions from different perspectives: ranging from very fast on-line optimization of simplified models to whole-body trajectory optimization through contacts. We have applied these methods on a hydraulically actuated and torque controlled quadruped robot, demonstrating different gaits and aperiodic dynamic motions in the real system.

Bio. Diego Pardo is a post-doctoral researcher in the Agile and Dexterous Robotics Lab (ADRL) of the Institute of Robotics and Intelligent Systems (IRIS) at the Swiss Federal Institute of Technology ETH in Zurich (2017). He received his Ph.D. degree in Robotics from UPC Barcelona Tech (2009). Diego has carried out postdoctoral research in the Istituto Italiano di Tecnologia – IIT in Genova (2014), the Institut de Robòtica I Informàtica Industrial – IRI in Barcelona (2012) and the Technical Research Centre for Dependency care and Autonomous Living in Barcelona (2011). He completed research stages at the École Nationale Supérieure de Techniques Avancées – ENSTA Paris Tech (2006) and the Università degli studi di Genova (2006). His contributions in robotics research exploit optimization and machine learning for the analysis and synthesis of complex robotic systems.

3.6 Dr. Francesco Nori - IIT, Italy.

Title: "iCub Whole-Body Control Through Force Regulation with Distributed Tactile Sensing"

Abstract. As opposed to traditional robotic applications that demanded for limited interaction and mobility, robots of the next generations will be required to coordinate physical interaction with physical mobility. Interaction always involve two components: the "self" (i.e. the robot) and the "other" (i.e. the interacting agent). Successful and energetically efficient interaction necessarily passes through modelling, estimating and controlling the mutual interaction between the self and the other. In a crescendo of complexity, research is expected to cope with increasingly complicated scenarios. On the one hand, robots (the self) are foreseen to become elastic and compliant. On the other hand, physical interaction is likely to occur not only with rigid and compliant environments but also, on the long run, with humans. Gradually, robots will require advanced decisional autonomy, adaptability and the ability to understand the intention of "others". To cope with scenarios and embodiments of increasing complexity, my research activities pursue the methodology described above with focus on three main areas: modelling, compliance and control. The final goal of these activities is to endow humanoids with advanced action and interaction capabilities. This goal is pursued with concurrent advances along two different but intertwined directions: on the one hand by advancing the theoretical understanding of the underlying scientific problems; on the other hand by a continuous optimisation and redesign of the existing hardware and software based on sound and solid theoretical bases.

Bio. Francesco was born in Padova in 1976. He received his D.Eng. degree (highest honors) from the University of Padova (Italy) in 2002. During the year 2002 he was a member of the UCLA Vision Lab as a visiting student under the supervision of Prof. Stefano Soatto, University of California Los Angeles. During this collaboration period he started a research activity in the field of computational vision and human motion tracking. In 2003 Francesco Nori started his Ph.D. under the supervision of Prof. Ruggero Frezza at the University of Padova, Italy. During this period the main topic of his research activity was modular control with special attention on biologically inspired control structures. Francesco Nori received his Ph.D. in Control and Dynamical Systems from the University of Padova (Italy) in 2005. In the year 2006 he moved to the University of Genova and started his PostDoc at the laboratory for integrated advanced robotics (LiraLab), beginning a fruitful collaboration with Prof. Giorgio Metta and Prof. Giulio

Sandini. In 2007 Francesco Nori has moved to the Italian Institute of technology where he is currently hired as a Tenure Track Researcher. His research interests are currently focused on whole-body motion control exploiting multiple (possibly compliant) contacts. With Giorgio Metta and Lorenzo Natale he is one of the key researchers involved in the iCub development, with specific focus on control and whole-body force regulation exploiting tactile information. Francesco is currently coordinating the H2020-EU project An.Dy (id. 731540); in the past he has been involved in two FP7-EU projects: CoDyCo as coordinator and Koroibot as principal investigator.

3.7 Prof. Taskin Padir - Northeastern University, USA.

Title: “Compositional Autonomy for Humanoid Robots”

Abstract. This talk will present results from recent experiments on NASA Johnson Space Center’s humanoid robot Valkyrie (R5). Our current research efforts include the development of planning and control algorithms for autonomous completion of tasks relevant to space exploration. We will introduce the notion of compositional autonomy and discuss future directions on dexterous manipulation and rough terrain locomotion for humanoid robots.

Bio. Taskin Padir is an Associate Professor in the College of Engineering at Northeastern University. His research interests include supervised autonomy for humanoid robots and shared control in human robot teams. He participated in the DARPA Robotics Challenge (DRC). Post DRC, he has been selected by NASA to receive one of two Valkyrie (R5) humanoid robots to advance the capabilities of the platform.

3.8 Prof. Maren Bennewitz - University of Bonn, Germany.

Title: “Perception and Motion Planning for Humanoids in 3D Environments”

Abstract. In this talk, we will first present our work on efficient footstep planning through cluttered 3D Environments. A variety of approaches exist that tackle the problem of humanoid locomotion. Simple dynamic walking controllers do not guarantee collision-free steps, whereas most existing footstep planners are not capable of providing results in real time. Thus, these methods cannot be used to react to sudden changes in the environment. We developed a real-time capable footstep planner that uses an adaptive 3D action set. When combined with fast planar region segmentation, it allows us to find valid footstep plans in complex scenes. In the second part of the talk, we will present recent results regarding full exploration of 3D environments with humanoids. We combine a next-best-view approach with inverse reachability maps to compute efficient motion plans for exploring unknown environments and for searching objects in known environments.

Bio. Maren Bennewitz is currently an associate professor for Computer Science at the University of Bonn and head of the humanoid robots laboratory. Her research focuses on robots navigating in human environments that consist of multiple levels and contain articulated as well as movable objects. She has contributed probabilistic methods for 3D environment modelling as well as for manipulation and navigation with wheeled and humanoid robots.

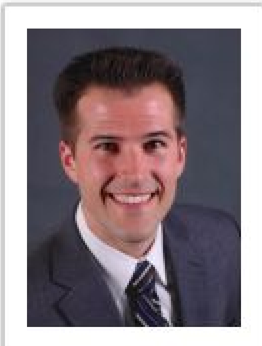
3.9 Alexander Stumpf - TU Darmstadt, Germany.

Title: "Towards Capable Open Source ROS-Frameworks for Real-Time Perception, World Modeling and Footstep Planning for Humanoid and Legged Robots"

Abstract. Bipedal locomotion capabilities have been improved remarkably in the last years. New control approaches as well as actuation hardware enable to cross robustly unstructured terrain with bipedal walkers. This new generation of walking robots require advanced perception and locomotion planning systems to cope with real world challenging terrain scenarios. This requires the application of novel and sophisticated approaches and therefore it is highly desirable to provide versatile software frameworks which can be deployed quickly at different robot platforms to break through the circle of re-inventions and -implementations. In this talk we will discuss recent research results regarding to our Footstep Planning Framework as well as our novel Perception and Multi-Sensor Framework "Mason" integrating TSDF representation efficiently which can even run on regular CPUs (http://wiki.ros.org/vigir_footstep_planning).

Bio. Alexander Stumpf has received his Master Degrees in Computer Science and Autonomous System in 2014 at the TU Darmstadt. Afterwards he has joined as Phd Student the Simulation, Systems Optimization and Robotics Group. His research topics are focused on perception and locomotion planning with application to real world scenarios using state of the art robot systems such as Atlas by BDI. During his research work he has already participated in various projects and competitions such as the Darpa Robotics Challenge (Team ViGIR and Team Hector), RoboCup (Team Hector) and ARGOS Challenge (Team Argonauts). These competitions addresses the use of robots in (semi-)autonomous search & rescue and industrial inspections tasks based on real world scenarios and thus, requires robust approaches in perception, planning and control.

3.10 Prof. Patrick Wensing - MIT, USA.



Title: "Real-time planning and control for the MIT Cheetah"

Abstract: The challenge of dynamic locomotion is well captured by the fact that high-speed gaits are never instantaneously balanced in a traditional sense. This challenge motivates the need for real-time predictive capabilities to unlock new levels of dynamic mobility in our robots. Towards this aim, the talk will focus on model-predictive control (MPC) for planning and stabilization of dynamic gaits in the MIT Cheetah 2. An MPC approach will be described for bounding in the sagittal plane, which has enabled autonomous jumping over obstacles up to 80% of leg length in hardware. To extend this framework for more general 3D gaits, a new approach of policy-regularized MPC (PR-MPC) will be discussed. This method has empirically been found to improve both the solution speed and outcomes of solving non-convex MPC optimization problems. PR-MPC is envisioned for application to a new robot, the MIT Cheetah 3, currently under final construction. The talk will conclude with a short description of this platform and ongoing efforts to validate the PR-MPC approach.

Bio: Patrick Wensing is a Postdoctoral Associate in the Biomimetic Robotics Laboratory within the Department of Mechanical Engineering at MIT. He received his Ph.D. in Electrical and Computer Engineering from The Ohio State University in 2014. He was awarded an NSF Graduate Research Fellowship for his dissertation research on balance control strategies for humanoid robots. At MIT, the results of his postdoctoral work on the MIT Cheetah robot have received considerable publicity worldwide.

3.11 Prof. Evangelos Papadopoulos - NTUA, Greece.

Title: "Legged Robot Control Using Passive Dynamics and Active Compliance"

Abstract. Two extremes in legged robot design are endurance and speed. Passive dynamics yield motions that can be the basis for low energy consumption locomotion, and therefore can provide the basis for low consumption controllers. In practice, robot losses and terrain compliance are critical parameters for the performance of legged locomotion.

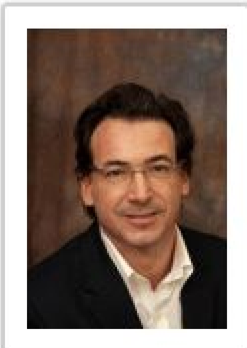
Based on passive dynamics analysis, a controller for a single actuator monopod hopping on rough compliant and inclined terrain will be presented that can follow both desired height and forward velocity commands. The correlation between terrain parameters and the CoT will be discussed, and useful conclusions, which can aid the understanding of the behavior of legged robots in realistic terrains, will be given. The passive dynamics approach is extended to the control of quadrupeds with revolute and prismatic torsos; results show close agreement with motions of quadrupeds in nature.

For achieving high speeds in quadrupeds, a control framework capable of generating dynamic quadrupedal gaits, employing biomimetic bean-shaped trajectories at the toes, and active compliance control at the actuated joints will be discussed. Simulations with biomimetic robots consisting of three-segment legs show stable and robust locomotion for a large range of forward velocities with various dynamic gaits (e.g. flying trot and gallop). Results from a trotting experiment will be presented that show that the robot is able to perform a complete locomotion scenario with acceleration from stance, to stable flying trot at constant speeds, and to deceleration back to stance, by regulating a single control parameter.

Bio. Evangelos Papadopoulos received his Diploma in Mechanical Engineering from the National Technical University of Athens, (NTUA), Greece, in 1981, and his M.S. (1983) and Ph.D. (1990) degrees in Mechanical Engineering from MIT. He joined the Department of Mechanical Engineering. at McGill University as an Assistant and Associate Professor. In 1997 he joined the NTUA, where he is currently a Professor of Mechanical Engineering. He teaches courses in Robotics, Controls, Mechatronics, Circuits and Systems, and Electromechanical Systems, and conducts research in space and underwater robotics, legged robots, microrobotics, mechatronics, haptics and prosthetics, design, and applied control, with funding from national, European, Canadian and industrial sources. He is a Fellow of the ASME, an

Associate Fellow of the AIAA, a Senior Member of the IEEE, the IFToMM, and the Technical Chamber of Greece.

3.12 Prof. Luis Sentis - University of Texas at Austin, USA.



Title: "Uncertainty in Human-Centered Robots"

Abstract. Uncertainty permeates in all control approaches and significantly complicates controller design. This is especially true for human-centered robots which rely on over-simplifications such as ignoring high-frequency behaviors or real-time delays to central computers. In this talk I join forces with two of my students to present detailed mathematical work on choosing structure for measuring uncertainty in a meaningful statistical sense, motivate the nature of uncertainty in hardware systems involving high performance series elastic actuators, and devise a planning and control framework that embraces uncertainty to external disturbances via reinforcement learning of locomotion responses.

Bio. Luis Sentis is an Associate Professor in Aerospace Engineering at the University of Texas at Austin and co-founder of Apptronik Systems. He received a Ph.D. in Electrical Engineering from Stanford University and was a La Caixa Foundation Fellow. He worked in Silicon Valley in the high-tech sector leading R&D projects in clean room automation. In Austin, he leads the Human Centered Robotics Laboratory, an experimental facility focusing on control and embodiment of humanoid robots. He writes extensively in areas related to realtime control of human-centered robots, design of high performance humanoid robots, and safety protocols in robotics. He was awarded the NASA Elite Team Award for his contributions to NASA's Johnson Space Center Software Robotics and Simulation Division.

4. Poster Abstracts

4.1 Nils Smit-Anseeuw, Audrow Nash, Ram Vasudevan, and C. David Remy - University of Michigan, USA.

Title: Safe Online Learning Using Barrier Functions

Abstract. We present a method for guaranteeing the safety of online learning schemes. The method uses barrier certificates and Sums-of-Squares programming to find a safe region of state space and a controller which renders that space positively invariant. This safe set and controller are then used to create “training wheels”, which can transform unsafe controllers into safe ones. These training wheels alter the given controller only when the state nears the edge of the safe region. Thus, except for where it would otherwise lead to falling, the original controller remains unchanged. For a given learning scheme, this projection is performed for each controller rollout to generate a safety guarantee for the scheme with minimal interference. We have simulation results for a simple car model and a simple hopping model, and plan to demonstrate safe learning of a hopping controller on the robot RAMone.

4.2 Alexander W. Winkler and Jonas Buchli - ETH Zurich, Switzerland.

Title: Quadruped Motion Generation through Optimization

Abstract. In this work we will present our newest research in legged locomotion using Trajectory Optimization. We formulate the important quantities (body and feet motion, contact state), the physical laws (unilateral contact forces) and kinematic restrictions (range of motion) in an Optimization Problem. The presented formulation can be seen as a generalization/combination of more traditional Zero-Moment-Point (ZMP) and Capture Point approaches. We don’t require a higher-level footstep planner, but the footholds are chosen simultaneously with the body optimization. The generated motions are physically consistent, due to our dynamics model of an Inverted Pendulum. Due to our minimal representation the optimization problem can be solved in milliseconds. We can show quadrupedal walk and trot executed on real systems.

4.3 Muhammad Bilal Khan and Muhammad Saqib Ilyas - Namal College, Pakistan and PSU, Thailand.

Title: A Quadruped Robot made of a Bio Sourced Material

Abstract. Nature brings us a number of ways to get inspired. In terms of mobility, it provides us different examples of natural systems with capabilities of locomotion e.g. a legged animal with four legs, a human with two legs, and insects with multiple set of legs etc. Taking inspiration from biology, we have developed a bio inspired quadruped robot. It is novel in a sense that its complete frame was manufactured using bio sourced materials i.e. Cedar wood, which is then further proved to be a moderately ideal choice, considering the scope of this work and developing it under low budget. Special servo configuration is also adding to better design practices. Off the shelf electronics and controller board makes it easier to get re-configured, and allows flexible choices for meeting relatively broader set of project objectives. This robot is initially tested in three stages: single leg experiments, single side pair of legs' experiments, and performing walk gait (all done separately inbound and outbound to the ground). Single leg kinematics are mapped to other legs with moderate variations. In overall, a bio inspired quadruped was designed, manufactured using bio sourced material i.e. wood, and experimented by performing in different stages leading to walk gait's implementation.

4.4 Carlos Mastalli, Michele Focchi, Ioannis Havoutis, Andreea Radulescu, Darwin G. Caldwell, and Claudio Semini - Istituto Italiano di Tecnologia (IIT), Italy, IDIAP Research Institute, Switzerland, and University of Oxford, UK.

Title: Trajectory Optimization and Dynamic Walking Adaptation for Rough Terrain Locomotion

Abstract. We present a trajectory and foothold optimization method that automatically adapts the walking gait for rough terrain locomotion. We jointly optimize the Center of Mass (CoM) motion and the foothold locations, while considering terrain conditions. We use a terrain costmap to quantify the desirability of a foothold location. We increase the gait's adaptability to the terrain by optimizing the step phase duration and modulating the trunk attitude, resulting in motions with guaranteed stability.

4.5 Janosch Machowinski, Arne Boeckmann, Sascha Arnold, Christoph Hertzberg, and Steffen Planthaber - DFKI and Universitat Bremen, Germany.

Title: Climbing Steep Inclines with a Six-Legged Robot using Locomotion Planning

Abstract. We present an approach to climb crater walls using the six-legged robot CREX (CRater EXplorer). The control architecture consists of a motion execution engine, a mapper, and a locomotion planner which maintains stability when climbing the crater wall.

4.6 Andreea Radulescu, Ioannis Havoutis, Darwin G. Caldwell, Claudio Semini - Istituto Italiano di Tecnologia (IIT), Italy, IDIAP Research Institute, Switzerland, and University of Oxford, UK.

Title: Whole-body Trajectory Optimization for Non-periodic Dynamic Motions in Legged Systems

Abstract. We present a whole-body optimization methodology for non-periodic tasks on quadrupedal systems (rearing and pose recovery). This approach delivers solutions involving multiple contacts without the need for predefined feet placements. The results obtained show the potential of such methods for motion synthesis in the context of complex tasks. The work described has been presented in detail in [1].

4.7 Dimitrios Kanoulas, Alexia Toumpa, Chengxu Zhou, Darwin G. Caldwell, and Nikos G. Tsagarakis - Istituto Italiano di Tecnologia (IIT), Italy.

Title: Vision-Based Footstep Localization for Rough Terrain Locomotion

Abstract. One of the main challenges in legged robot locomotion is the localization of footstep contacts in rough and rocky outdoors environments. Sparsity of foothold affordances is one of the main advantages of robots with limps over the other types of robotic systems. We present a 3D perceptual localization and mapping system for modeling, localizing, and mapping sparse local surfaces in rough terrain based on 3D curved patches of the size and shape of the robot's foot. Range sensing has been used to reconstruct the environment using the Moving Volume KinectFusion (i.e. a dense volumetric range data fusion system) and fit a set of patches to the close-by surfaces. Then a contact analysis between the foot and the environment patch takes place, giving a set of good contact footholds. This set of contacts could potentially be fed to a graph-based footstep planner in a higher level locomotion module. We present some real-time experimental foot placements (i.e. stepping) results on rough terrain for a mini-biped (RPBP) and a half-size (COMAN) humanoid robot using different trajectory planning methods.

4.8 Andrew Short and Tirthankar Bandyopadhyay - University of Wollongong and CSIRO, Australia.

Title: Legged Motion Planning in Complex 3D Environments

Abstract. Inspection tasks require robots to traverse complicated real-world structured environments such as shown in Fig. 1a. The robot in Fig. 1b has been developed with magnetic feet to navigate such environments, but motion planning for the robot presents significant challenges. Gaited locomotion planners are not suitable due to the complex manoeuvres

required and hence non-gaited full-body motion planning is required. We present a planning approach which uses a pre-computed Contact Dynamic Roadmap (CDRM) data structure to allow for rapid foothold configuration evaluation, enabling online non-gaited motion planning in complex 3D environments.

4.9 Maozhen Wang, Murphy Wonsick, Velin Dimitrov, Xianchao Long, Taşkın Padır - Northeastern university, USA.

Title: In-situ Terrain Estimation and Stability Analysis for Bipedal Humanoid

Abstract. The work we present focuses on classification of the ground type which can be leveraged to improve the stability of humanoid robots on deformable terrain. One way to accomplish this is by estimating the ground properties using proprioceptive sensor feedback from the foot of the robot. We present our experimental procedures in detail and data with NASA's humanoid robot, Valkyrie, performing a set of pre-specified motions on different terrains, including concrete, foam, mulch, rubber and sand. A relative stiffness for each terrain is modelled based on the experimental data resulting in the prediction of the ground type. We will also present our ongoing work on stability analysis of different step size selection on deformable terrains. A comparison of COM trajectory projection on support polygon of Valkyrie walking on solid ground and deformable terrains with different step size will be presented. From this comparison, it is worth noting that an uncentered COM position may cause deformation of support polygon, which should be avoided. We will present our approaching of adjusting the COM position by selecting proper step size and transit time on deformable terrain. We expect the experimental data gathered in our laboratory setting can be used to design and improve the controllers for traversing different types of terrain.

4.10 Oliver Urbann and Ingmar Schwarz - Universität Bayreuth, Germany.

Title: An Alternative Derivation of the Linear Inverted Pendulum Model

Abstract. The Linear Inverted Pendulum model is a well-known and popular approach for biped gait planning as it provides the relation between the Zero Moment Point (ZMP) based on a single center of mass (CoM). It is linear and can therefore be applied to various approaches to generate a motion of the CoM given a desired ZMP trajectory. However, for beginners in research or in education the derivation as presented in [1] can be confusing and presents many details that are not required. Here we intend to present two derivations. The first is an intuitive approach to the ZMP by explaining the concept using a beam balance. In the following we derive the ZMP of the Linear Inverted Pendulum model as presented in [1].

4.11 Simona Nobili and Maurice Fallon - University of Edinburgh and University of Oxford, UK.

Title: Multi-sensor Perception for Robust Localization of Dynamic Robots

Abstract. State estimation strategies for dynamic robots are typically based on inertial sensing and leg kinematics, and are affected by continuous drift. Laser measurements can be used to compensate for this drift via 3D scene registration. In this work, we present a system for robust localization of floating-base robots. The approach fuses inertial, kinematic, stereo vision and laser signal sources to achieve robust and accurate continuous estimation of the robots base link states (pose and velocity), in the presence of challenges such as limited field of view, uneven terrains and crowds of people in the environment, as well as disturbances such as slips and missteps. Our solution builds upon a modular inertial-driven Extended Kalman Filter based state estimator, with additional inputs from stereo visual odometry and laser registration. We show that the simultaneous use of both stereo vision and laser helps combat operational issues which occur in real applications.

4.12 Marco Camurri, Maurice Fallon, Victor Barasuol, Darwin G. Caldwell, and Claudio Semini - Istituto Italiano di Tecnologia (IIT), Italy and University of Oxford, UK.

Title: State Estimation in the Loop for Accurate Base Pose and Velocity Tracking of Dynamic Legged Robots

Abstract. In this work, we present the fusion of proprioceptive and exteroceptive sensing to achieve accurate base pose and velocity tracking of the 85 kg quadruped robot HyQ. By means of a modular Extended Kalman Filter (EKF) framework, we fuse (at high frequency) the information from an Inertial Measurement Unit (IMU) and a probabilistic Leg Odometry (LO) module to achieve smooth and accurate velocity estimation. For accurate pose estimation, we incorporate low-frequency pose updates to the filter through a scan matcher module. These two states (pose and velocity) are then tightly coupled with the trunk controller, in order to keep the robot in place while trotting, despite considerable disturbances induced by a human operator.

4.13 Milad Shafiee-Ashtiani, Aghil Yousefi-Koma, Masoud Shariat-Panahi, Majid Khadiv - University of Tehran, Iran.

Title: Robust bipedal Locomotion Control based on Model Predictive Control and Divergent Component of Motion

Abstract. In order to realize the dream of employing humanoid robots in our real world, developing a unified, robust and versatile framework for bipedal locomotion control is essential. To take a step toward this goal, we develop a framework for balance recovery of a biped robot based on Model predictive Control(MPC) and Divergent Component of Motion(DCM). We employ a single MPC which uses a combination of Center of Pressure (CoP) manipulation, step adjustment, and Centroidal Moment Pivot (CMP) modulation to design a robust locomotion controller. Furthermore, we exploit the concept of time-varying DCM to generalize our walking controller for walking on uneven surfaces. Using our scheme, a robust walking controller is designed which can be implemented on robots with different control authorities, for walking on various environments, e.g. uneven terrains or surfaces with a very limited feasible area for stepping.

4.14 Yue Hu, and Katja Mombaur - Heidelberg University, Germany.

Title: Whole-body walking motion generation with optimal control

Abstract. Walking is still an open challenging problem for humanoid robots, where reduced models such as the inverted pendulum, the table-cart and the spring loaded inverted pendulum are often preferred due to the faster computations times and easier dynamics. Despite their popularity, it is known that such models do not allow to exploit the whole-body dynamics of the robot, resulting in walking motions where the upper body does not perform any motion.

In order to take into account the whole-body dynamics, we use optimal control to generate whole-body walking motions. In particular, we use the model of the humanoid robot HeiCub, which is a reduced version of the humanoid robot iCub without arms and head and with legs designed for locomotion tasks. The HeiCub is located in Heidelberg and was built as part of the European Project KoroiBot to perform walking experiments. In a previous work we analysed the walking capabilities of the robot in several environments by means of a table-cart based pattern generator and gathered information about the capabilities and limitations of the robot that have to be taken into account in optimal control problems under the form of constraints, parameters and objectives.

Safe Online Learning Using Barrier Functions

Nils Smit-Anseeuw, Audrow Nash, Ram Vasudevan, and C. David Remy

***Abstract*— We present a method for guaranteeing the safety of online learning schemes. The method uses barrier certificates and Sums-of-Squares programming to find a safe region of state space and a controller which renders that space positively invariant. This safe set and controller are then used to create "training wheels", which can transform unsafe controllers into safe ones. These training wheels alter the given controller only when the state nears the edge of the safe region. Thus, except for where it would otherwise lead to falling, the original controller remains unchanged. For a given learning scheme, this projection is performed for each controller rollout to generate a safety guarantee for the scheme with minimal interference. We have simulation results for a simple car model and a simple hopping model, and plan to demonstrate safe learning of a hopping controller on the robot RAM*one*.**

I. Introduction

Online learning is a valuable tool for achieving high performance behaviour in physical systems when modelling accuracy is limited. This is particularly true for legged robots since it is difficult to accurately model contact events. However, such learning schemes can be particularly challenging for legged robots due to the high cost of falling (which can require lengthy hardware repairs). As such, successful learning implementations on walking robots have been largely limited to hardware in which either the likelihood or the cost of falling is low (e.g. [1], [2]).

One way to mitigate the risk of falling is to determine the space of "safe" controllers and states. That is, the space of initial conditions and control inputs which avoid failure states for all time. Once found, we can restrict a given learning scheme to search for controllers within this space.

In this work, we use polynomial barrier functions to find the set of safe states. We use this set to compute a mask that can take any unsafe controller and render it safe with minimal modification. This approach is similar to that in [3], in which barrier functions are used to guarantee the safety of Lyapunov-based controllers.

II. Methods

The class of systems we consider in this paper are those with dynamics of the form:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}) + \mathbf{g_u}(\mathbf{x})\mathbf{u} + \mathbf{g_d}(\mathbf{x})\mathbf{d}. \tag{1}$$

Where $\mathbf{f}$, $\mathbf{g_u}$ and $\mathbf{g_d}$ are polynomials in $\mathbf{x}$, $\mathbf{u}$ is the control input, which takes values from the bounded set U, and $\mathbf{d}$ is the uncontrolled, time varying disturbance input which takes values from the bounded set D.

We begin by defining the set of safe states:

$$X_s = \{\mathbf{x_0} \mid \exists \mathbf{u}(\mathbf{x}) \in U \text{ s.t. } \mathbf{x}(\mathbf{x_0}, \mathbf{u}(\mathbf{x}), \mathbf{d}(t), \tau) \notin X_F \\ \forall \tau \in [0, \infty), \forall \mathbf{d}(t) \in D\}. \tag{2}$$

Where X_f are the failure states, and the notation $\mathbf{x}(\mathbf{x_0}, \mathbf{u}(\mathbf{x}), \mathbf{d}(t), \tau)$ represents the flow forward of the state $\mathbf{x_0}$ under controller $\mathbf{u}(\mathbf{x})$ and disturbanc $\mathbf{d}(t)$ after time τ. This can be seen as the largest forward control invariant set [3] that doesn't include the failure states.

To find X_s, we use a barrier function approach similar to that in [4]. This approach results in a polynomial $\mathbf{v}(\mathbf{x})$ and a controller $\mathbf{u_s}(\mathbf{x})$ that renders the 0 superlevel set of $\mathbf{v}$ forward invariant (i.e. $\{\mathbf{x} | \mathbf{v}(\mathbf{x}) \geq 0\} \subset X_s$).

The only requirement for forward invariance of the set X_s is that the flow of the system is inward on the boundary. This means that any controller will be safe so long as it enforces this flow condition on the edge of the safe set. Thus we define a safety mask that modifies controllers only in the neighborhood of $v(\mathbf{x}) = 0$. Since we know that $\mathbf{u_s}(\mathbf{x})$ satisfies the flow condition, we smoothly interpolate between this controller on the boundary of the safe set and the initial controller in the interior. This gives us a safe controller that matches the initial controller everywhere except where it would otherwise lead to falling.

Once this safety mask has been computed, the result can be applied in real-time to arbitrary control input. Simply monitor the state until it approaches the boundary of X_s, then follow the interpolation scheme to determine the safe input. As such, this approach can be used as a last step in any learning scheme to ensure that each controller used on the hardware is safe.

III. Preliminary Results and Future Work

At the time of this abstract, we have implemented this method on both a Dubin's car and a 1-dimensional hopper.

The next goal is to use this scheme to conduct safe online learning of a linear hopping controller on the robot RAM*one*. To do this, we we will extend the 1d hopper model to include a massive foot and a flight phase. Once the safe set of controllers is computed for this model, we will use a CMA-ES policy learning scheme to learn a controller online that hops to a desired height with minimal energy consumption.

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Quadruped Motion Generation through Optimization

Alexander W. Winkler and Jonas Buchli

***Abstract*— In this work we will present our newest research in legged locomotion using Trajectory Optimization. We formulate the important quantities (body and feet motion, contact state), the physical laws (unilateral contact forces) and kinematic restrictions (range of motion) in an Optimization Problem. The presented formulation can be seen as a generalization/combination of more traditional Zero-Moment-Point (ZMP) and Capture Point approaches. We don't require a higher-level footstep planner, but the footholds are chosen simultaneously with the body optimization. The generated motions are physically consistent, due to our dynamics model of an Inverted Pendulum. Due to our minimal representation the optimization problem can be solved in milliseconds. We can show quadrupedal walk and trot executed on real systems.**

I. Introduction

Legged locomotion is a difficult task, partially because feet can only push and not pull on the ground (=unilateral contact forces). A stream of successful approaches able to deal with this restriction are based on ZMP [1] and Capture Point [2]. Approaches based on the ZMP are usually used for biped or quadruped walking [3] and approaches based on Capture Point for more dynamical motions, e.g. quadruped trotting [4]. Although these approaches work well in practice, they are often still very specific to one type of gait. We generalize this through the use of Trajectory Optimization (TO) formulation, which allows us to generate various gaits with only one framework. This is our newest stream of research currently under review for RA-L.

The presented approach formulates a continuous-time TO problem

$$
\begin{aligned}
&\text{find} && \mathbf{x}(t), \mathbf{u}(t) && && \text{(1a)}\\
&\text{subject to} && \mathbf{x}(0) - \mathbf{x}_0 = 0 && \text{(given initial state)} && \text{(1b)}\\
& && \dot{\mathbf{x}}(t) - \mathbf{f}(\mathbf{x}(t), \mathbf{u}(t)) = 0 && \text{(dynamic model)} && \text{(1c)}\\
& && \mathbf{h}(\mathbf{x}(t), \mathbf{u}(t)) \leq 0 && \text{(path constraints)} && \text{(1d)}\\
& && \mathbf{x}(T) - \mathbf{x}_T = 0 && \text{(desired final state)} && \text{(1e)}\\
& && \mathbf{x}(t), \mathbf{u}(t) = \arg\min J(\mathbf{x}(t), \mathbf{u}(t)). && && \text{(1f)}
\end{aligned}
$$

This says, we want to obtain the inputs $\mathbf{u}(t)$ that generate the motion $\mathbf{x}(t)$ from an initial state $\mathbf{x}_0$ to a desired goal state $\mathbf{x}_T$ in time T for a robot described by the system dynamics $\mathbf{f}(\mathbf{x}(t), \mathbf{u}(t)$, while respecting some constraints $\mathbf{h} \leq 0$ and optimizing a performance criteria J. We model the robot's dynamics as a Linear Inverted Pendulum. The touchdown point of the pendulum represents the ZMP or Center of Pressure (CoP). This can be modified by applying joint torques, which in turn generate contact forces which change

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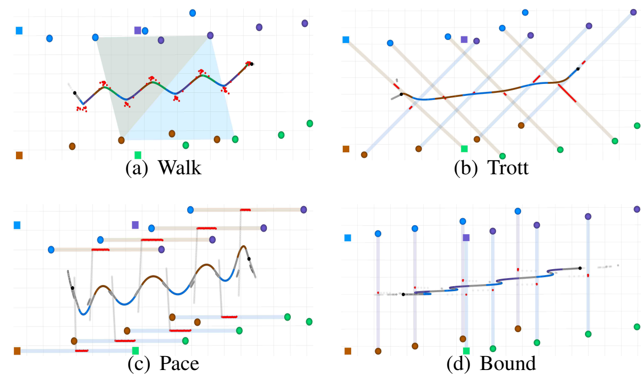

Fig. 1. Top down view of the generated motions for a quadruped robot moving from left→right. The CoM motion is shown by the solid line. The support area for each phase is shown by the transparent areas. The optimized CoP positions $\mathbf{u}(t)$ that drive the system are shown in red and always lie inside the support area.

the CoP. Therefore we view the CoP as the controllable input $\mathbf{u}(t)$, an abstraction for joint torques and contact forces.

The Optimization problem can be seen as follows: The CoM motion is generated by shifting the CoP $\mathbf{u}$. However, $\mathbf{u}$ can only lie in the convex hull of the legs in contact (unilateral forces). Additionally, the position of each leg must always be inside it's range of motion. The optimization problem consist of shifting around the position of the footholds, to allow inputs that drive the robot from an initial position $\mathbf{x}_0$ to a desired goal position $\mathbf{x}_T$ in time T.

This formulation allows us to generate motions for quadruped walk, trot, pace and bound (see Fig. 1) in milliseconds and execute walk and trot on real systems. We believe that this intermediate approach between full-body Trajectory Optimization and traditional ZMP/Capture Point motion generation could help narrow the gap between simulation and real hardware.

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A Quadruped Robot made of a Bio Sourced Material

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Summary

Nature brings us a number of ways to get inspired. In terms of mobility, it provides us different examples of natural systems with capabilities of locomotion e.g. a legged animal with four legs, a human with two legs, and insects with multiple set of legs etc. Taking inspiration from biology, we have developed a bio inspired quadruped robot. It is novel in a sense that its complete frame was manufactured using bio sourced materials i.e. Cedar wood, which is then further proved to be a moderately ideal choice, considering the scope of this work and developing it under low budget. Special servo configuration is also adding to better design practices. Off the shelf electronics and controller board makes it easier to get re-configured, and allows flexible choices for meeting relatively broader set of project objectives. This robot is initially tested in three stages: single leg experiments, single side pair of legs' experiments, and performing walk gait (all done separately inbound and outbound to the ground). Single leg kinematics are mapped to other legs with moderate variations. In overall, a bio inspired quadruped was designed, manufactured using bio sourced material i.e. wood, and experimented by performing in different stages leading to walk gait's implementation.

Motivation

A legged robot can be used to access places that are not accessible by humans or by wheeled mobile robots. Taking inspiration from biology where a number of mechanisms exist to perform locomotion, a number of legged robots are built. They are different; from their work goal to design. Bringing ideas from existing mechanisms in nature, we can develop a machine that can perform following activities (when working with full efficiency):

- To access places and perform different tasks in a hazardous environment.
- To take care of a forest where they (legged robots) can be used to minimize the damage of a spread fire.
- Work in war zones to carry a wounded soldier/human.
- To help in search and rescue during a calamity.
- Inspection of sites that are dangerous to get inspected by a human physically, etc.

Results

Experiment 1: In our first experiment, we implemented a walking trajectory on a single leg prototype using C code. This experiment was done with prototype leg hanging tightly above the ground (a pre-cautionary measure to minimize possibilities of any damage if servos or controller behaves in an undesirable way). We used different values of angles for both joints in order to get different behaviors. Finally, by tuning this 2 DOF leg on two different ranges of angles and adding open loop control, we were able to get a close to ellipse trajectory at the edge of the foot. Figure 1 indicates result of this experiment.

Experiment 2: After implementing our experiment 1 on a single leg, we took our learning to engage other three legs by replicating results. Due to mechanical configuration of legs as shown in fig.2, our angles used for leg 1 (previously) are useful for other leg mounted on same side, and with same configuration. For the opposite pair of legs, we formulated another set of joint values that can provide similar trajectory for a complete walk pattern of this quadruped machine.

Experiment 3: Finally, a walk gait implementation was achieved. To perform a walk gait, we have added some time delays in between of each step and synced walk pattern to expected foot print based pattern. Considering scope of this work, this porotype robot is limited to climb very small height obstacles as of yet (Figure 5 shows current height that it can climb with initially set joint angles), but we can increase this considerably by re-evaluating PWM definitions and by allowing more complexity to gait design with a tradeoff on efficiency and cost.

Figures

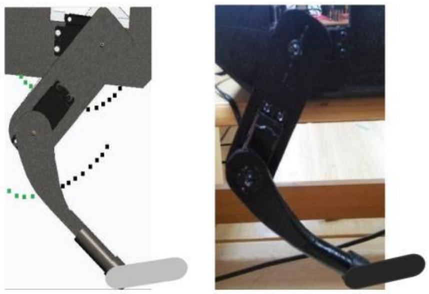

Fig. 1: Trajectories achieved during experiment 1

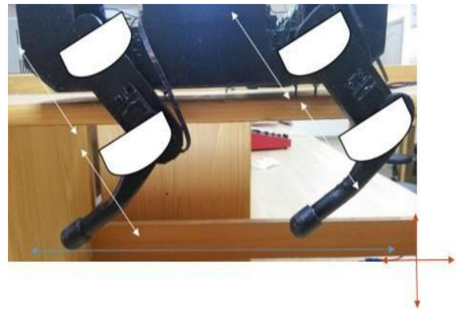

Fig. 2: Motor configuration

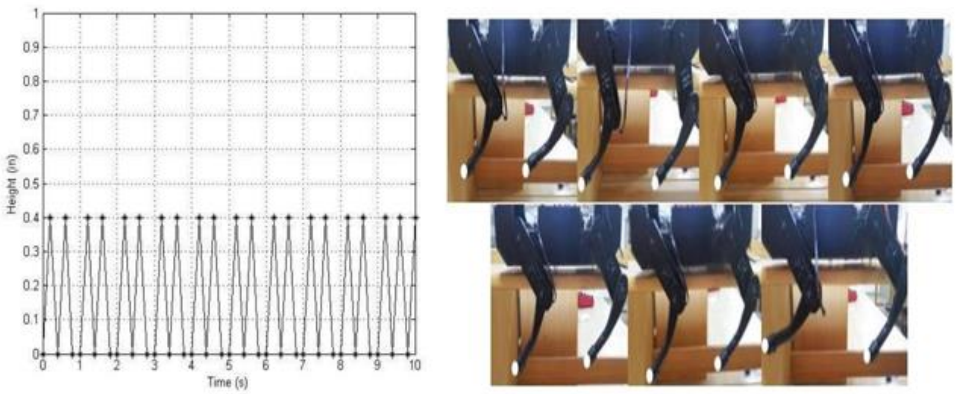

Fig. 5: Variation at the feet edge w.r.t height (graph and frame sequence)

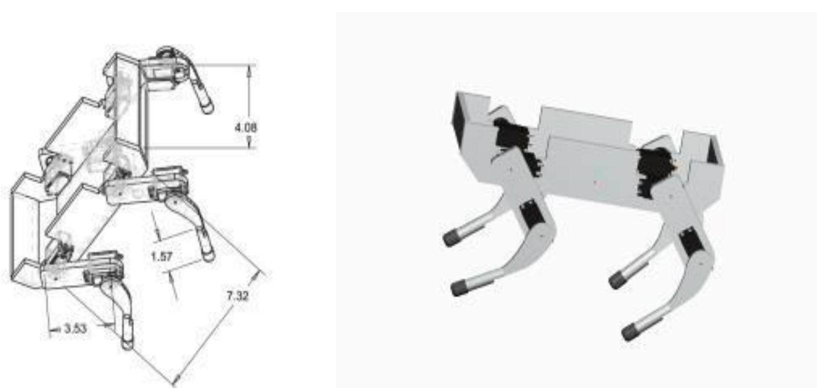

Fig. 6: CAD model and robot's drawing

Trajectory Optimization and Dynamic Walking Adaptation for Rough Terrain Locomotion

Carlos Mastalli[1], Michele Focchi[1], Ioannis Havoutis[2,3], Andreea Radulescu[1], Darwin G. Caldwell[1], Claudio Semini[1]

***Abstract*— We present a trajectory and foothold optimization method that automatically adapts the walking gait for rough terrain locomotion. We jointly optimize the Center of Mass (CoM) motion and the foothold locations, while considering terrain conditions. We use a terrain costmap to quantify the desirability of a foothold location. We increase the gait's adaptability to the terrain by optimizing the step phase duration and modulating the trunk attitude, resulting in motions with guaranteed stability. For more details see [1].**

I. Introduction

Legged vehicles present a potential advantage over traditional wheeled systems since they offer greater mobility in rough and challenging terrain. However, most legged robots are still confined to structured and flat terrain. Recently, trajectory optimization with contacts gained a lot of attention in the legged robotics community [2][3][4][5]. These optimization problems are often hard to solve, and the automatic synthesis of behaviors may be limited by the non-convexity of such domains, e.g. due to local minima. Adaptation and automatic gait discovery can be solved using low-dimensional parametric models that capture the most relevant dynamics [6]. In fact, a combination of low-dimensional parametric models with a stochastic-based exploration may be able to generate effective behaviors even without warm-starting the exploration.

II. Our approach

Our trajectory optimization method for quadrupedal robots addresses the locomotion as a coupled planning problem of CoM motions and footholds, where the foothold locations are selected using a terrain costmap while the trunk height and attitude are adapted for coping with different terrain elevations (see Fig. 1) [1]. First, we optimize a sequence of control parameters (the Center of Pressure (CoP) displacement, the phase duration and the foothold locations) given the terrain costmap. Then, we jointly generate the CoM trajectory and the swing-leg trajectory using a sequence of parametric preview models and the terrain elevation map. To realize the low-dimensional plan, the controller selects appropriate torque commands, which are computed by the combination of a trunk controller with a joint-space torque controller.

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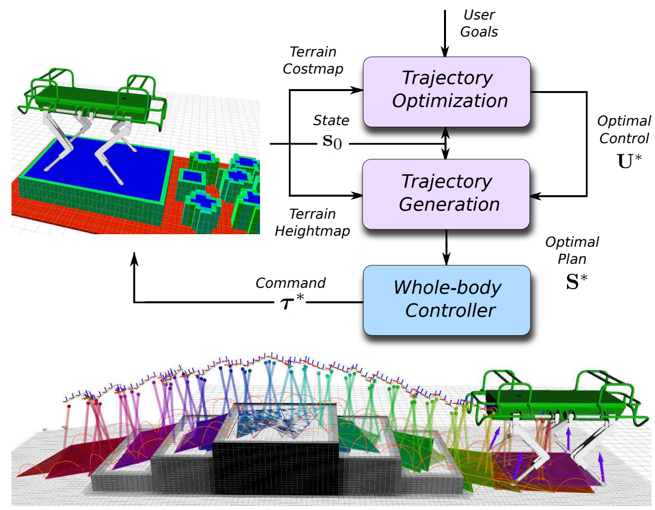

Fig. 1. Overview of the trajectory optimization framework for locomotion on rough terrain [1]. We compute offline an optimal control sequence $\mathbf{U}^*$ given the user's goals, the actual state $\mathbf{s}_0$ and the terrain costmap. Given this optimal control sequence, we generate the optimal plan $\mathbf{S}^*$ that copes with the changes in the terrain elevation through trunk attitude planning. Lastly, the whole-body controller calculates the joint torques $\boldsymbol{\tau}^*$ that satisfy friction-cone constraints.

The proposed trajectory optimization method increases the locomotion capabilities compared to our previous framework [7][8].

Given an initial state $\mathbf{s}_0$, we optimize a sequence of control parameters inside a predefined horizon, and apply the optimal control of the current phase. We find the sequence of control parameters $\mathbf{U}^*$, through an unconstrained optimization problem, given the desired user commands (trunk velocities):

$$\mathbf{U}^* = \underset{\mathbf{U}}{\operatorname{argmin}} \sum_j \omega_j g_j(\mathbf{S}(\mathbf{U})), \tag{1}$$

where $\mathbf{S} = \begin{bmatrix}\mathbf{s}_1 & \cdots & \mathbf{s}_N\end{bmatrix}$ is the sequence of preview states and N is the planning horizon. The preview state is defined by the CoM position and velocity $(\mathbf{x}, \dot{\mathbf{x}})$, CoP position $\mathbf{p}$ and the stance support region $\mathbf{F}$, i.e. $\mathbf{s} = \begin{bmatrix}\mathbf{x} & \dot{\mathbf{x}} & \mathbf{p} & \mathbf{F}\end{bmatrix}$. Where $\mathbf{F} = \begin{bmatrix}\mathbf{f}_1 & \cdots & \mathbf{f}_j\end{bmatrix}$ is defined by the position of the active feet $\mathbf{f}_j$. The cost functions and soft-constraints $g_i(\mathbf{S})$ describe: *1*) the user command tracking with step duration and length, and travel direction, *2*) the CoM energy, *3*) the terrain cost, *4*) stability soft-constraint, the i.e. CoP condition, and *5*) the preview model soft-constraint, i.e. the linear inverted pendulum.

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Climbing Steep Inclines with a Six-Legged Robot using Locomotion Planning

Janosch Machowinski[2] Arne Boeckmann[2] Sascha Arnold[1] Christoph Hertzberg[2] Steffen Planthaber[1]

Abstract— **We present an approach to climb crater walls using the six-legged robot CREX (CRater EXplorer).**

The control architecture consists of a motion execution engine, a mapper, and a locomotion planner which maintains stability when climbing the crater wall.

I. Introduction

Legged robots have several advantages in comparison to wheeled robots when climbing unstructured terrain. One of them is that they are able to freely place their feet in order to maximize stability and minimize slip. Here we present our approach to exploit these advantages by combining a local mapper with a locomotion planner.

II. Local Mapping

We model the local 3D environment of the robot using a truncated signed distance function (TSDF). Each distance measurement sensed by the LiDAR is ray-traced through a voxel grid. In each cell the signed distance to the surface and measurement uncertainty is updated using the Kalman update rule. To compute the optimal foot placement on the surface a mesh is reconstructed on the basis of the voxel grid using the Marching Cubes algorithm [1] also considering the uncertainties of the integrated measurements. Since this approach models free space, while the actual surface information is reconstructed, it is more robust against outliers, dynamic changes in the environment and the error in the odometry of the robot.

III. Locomotion Planner

The locomotion planner is designed, to move the robot by a given motion command, while keeping static stability. This is achieved by using a simple motion pattern in combination with a planning approach. The motion pattern consists of five phases:

1) movement of the body
2) tilt/pan for liftoff
3) relaxation of the liftoff spring
4) single leg movement
5) tilt/pan for body movement

To minimize slip during the movement phase, the robot utilizes a force balancing approach, to achieve ground contact with all feet.

After every motion phase, an A-Star planner is used to preplan a series of steps that maintain static stability. The termination criteria for the A-Star planner is that every foot is moved at least once. During the planning phase the local map is used, to sample touchdown positions on the surface of the map. The next lift-off pose and touchdown position are then determined from the result of the planning and given to the motion execution. To avoid ground collisions during leg movement, a collision-free trajectory above the map is computed.

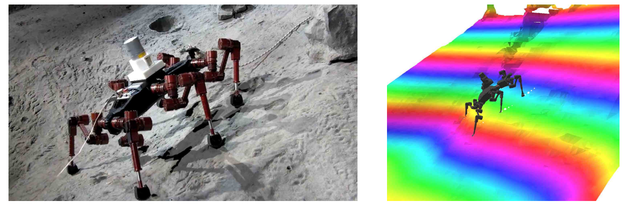

Fig. 1. Left: CREX is a six-legged robot with 24 degrees of freedom (four revolute joints per leg). It has rubber feet attached to a spring-suspended lower leg. The length of the lower leg is measured by a linear encoder, so the kinematics can be calculated accurately. Forces and torques in 6 DOF are measured at the body mount of each leg. It utilizes a *Velodyne HDL-32E* LiDAR for localization and local mapping.
Right: CREX inside local map. Height is encoded by different colors (one cycle per meter). White dots mark candidate foot positions.

IV. Preliminary results

Using this approach, the CREX Robot was repeatedly able to climb up a distance of 6 meters on a moon-like crater with an inclination of 35°. The artificial crater is a solid mock-up of a lunar crater explicitly created for such experiments (Fig. 1).

Acknowledgement

This approach was developed within the project Entern [2] which targets autonomous crater and cave exploration.

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Whole-body Trajectory Optimization for Non-periodic Dynamic Motions in Legged Systems

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Abstract— **We present a whole-body optimization methodology for non-periodic tasks on quadrupedal systems (rearing and pose recovery). This approach delivers solutions involving multiple contacts without the need for predefined feet placements. The results obtained show the potential of such methods for motion synthesis in the context of complex tasks. The work described has been presented in detail in [1].**

I. INTRODUCTION

A fully autonomous locomotion system would have to complete a heterogeneous range of tasks, some of which would require non-periodic solutions which could be described as single-shot movements. Examples in quadrupedal locomotion include rearing, overcoming an obstacle or gap, squat-jumping in place, posture and fall recovery.

Currently, the majority of robotic systems operating in an unsafe, disorganized and cluttered environment (e.g., search and rescue missions, disaster response, nuclear decommissioning) have to rely heavily on teleoperation in order to achieve their objectives. Optimization and learning methodologies could deliver solutions for such scenarios by using high-level task specifications, in the form of an evaluation criterion of the overall performance of the emerging behavior.

II. STATE OF THE ART

The relationship between learning and optimization has been under analysis for a long time [2], [3]. However, it is only in the recent past that their use has been extended to high dimensional problems, common to modern multi-degree-of-freedom (DoF) robotics applications. Various optimization techniques were proposed for dealing with multiple contact events. One popular approach is based on online Model Predictive Control (MPC) [4], [5]. Methods such as Policy Improvement with Path Integrals (PI^2) [6], based on stochastic optimal control principles, were also successful in generating optimal solutions for robotic systems [7], [8]. The Covariance Matrix Adaptation (CMA) algorithm [9] has been similarly used to generate whole body movements [10].

Another major challenge is solving such high-level tasks without the use of pre-defined heuristics such as hard-coded sequences or feet placements [11]. In spite of the significant efforts in the area of fall avoidance, comparatively little research has focused on developing generalized self-righting techniques [12], [13].

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III. OUR METHODOLOGY

We address this issue by providing a generalized approach for delivering whole body movement solutions. We use a CMA evolution strategy based procedure to address dynamic non-periodic tasks for a quadrupedal robotic system: rearing and posture recovery. A direct optimization technique on the time-parametrized joint or torque trajectories would involve an inconveniently large search space. Hence, we use a parametrized policy to encode these profiles, represented as a weighted average of Gaussian kernels: $f(t) = \sum_{i=1}^{M} w_i\phi_i(t) / \sum_{i=1}^{M} \phi_i(t)$, where w_i are the weights associated with each kernel $\phi_i,\ \ i \in [1, M]$, defined by: $\phi_i(t) = exp(-\frac{1}{2\sigma^2}(t - \mu_i))$.

The CMA algorithm is then used to optimize the weights of all policies according to a task specific cost function, applied to the whole body trajectory generated through the parametrized policy. In our experiments we use 12 such representations, one for each DoF of the quadrupedal system.

IV. SIMULATION RESULTS

Using a realistic simulation of the hydraulically actuated HyQ2Max quadruped [14], we investigate two distinctive tasks: rearing and posture recovery. We employ a generalized form for the cost function, while adjusting the relative gains of each term according to the current task. Although tuning the relative weights of such cost functions is a manual process, a heuristic encoding of the same behavior would require a significantly higher effort.

By exploiting the whole body model in order to obtain the solution, the optimization does not have to depend upon a pre-specified solution guess and can overcome errors caused by the use of simplified models. The resultant trajectories and the accuracy with which the user defined goals are achieved are reflecting the relative ratios of the weights on the individual cost function terms.

V. CONCLUSION AND FUTURE DIRECTIONS

The approach is able to provide trajectory solutions which involve multiple contacts, without any predefined feet placement heuristics (e.g., contact points, timing or order of succession). We aim to extend the methodology to deliver an optimal duration for the given task, while the final pose is fully determined, based on subsequent requirements. In the long term we aspire to develop a general tool for generating optimal dynamic whole-body motions that are not necessarily periodic in nature.

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Vision-Based Footstep Localization for Rough Terrain Locomotion

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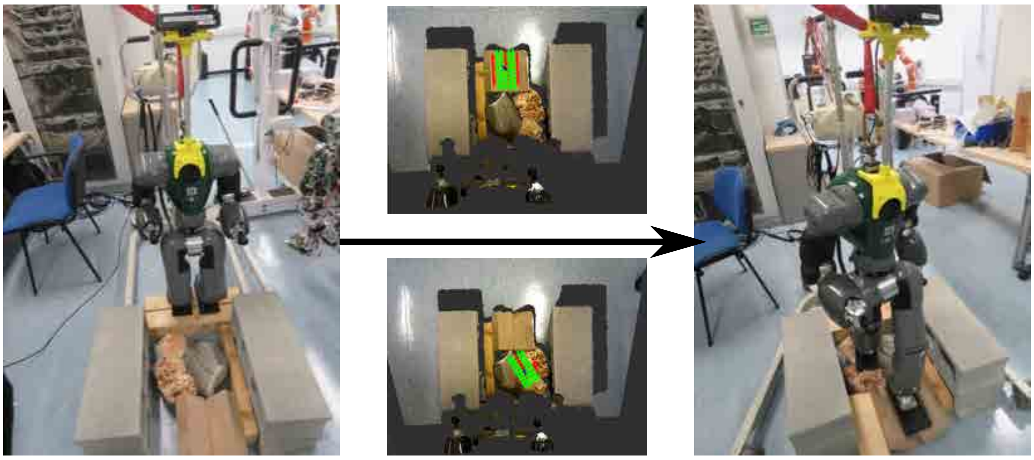
Abstract

One of the main challenges in legged robot locomotion is the localization of footstep contacts in rough and rocky outdoors environments [1]. Sparsity of foothold affordances is one of the main advantages of robots with limps over the other types of robotic systems [2]. We present a 3D perceptual localization and mapping system for modeling, localizing, and mapping sparse local surfaces in rough terrain based on 3D curved patches of the size and shape of the robot's foot [3]. Range sensing has been used to reconstruct the environment and fit a set of patches to the close-by surfaces. Then a contact analysis between the foot and the environment patch takes place, giving a set of good contact footholds [4]. This set of contacts could potentially be fed to a graph-based footstep planner in a higher level locomotion module. We present some real-time experimental foot placements (i.e. stepping) results on rough terrain for a mini-biped (RPBP) and a half-size (COMAN) humanoid robot using different trajectory planning methods. The whole system has been implemented as the Surface Patch Library (SPL), with code available on our website [5].



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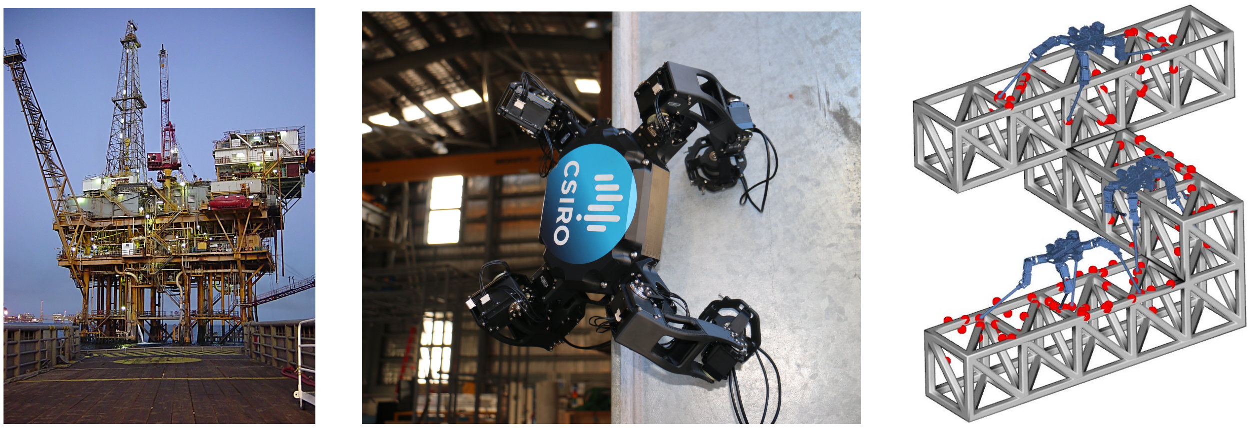
Legged Motion Planning in Complex 3D Environments

Andrew Short[1]and Tirthankar Bandyopadhyay[2]



(a) (b) (c)

Figure 1: (a) A typical oil rig structure[[1]] which presents challenges for comprehensive inspection, (b) a quadruped robot with magnetic feet designed for inspecting such structures, (c) snapshots of a simulation of the full body planning for the quadruped traversing a complex 3D truss structure.

Inspection tasks require robots to traverse complicated real-world structured environments such as shown in Fig. 1a. The robot in Fig. 1b has been developed with magnetic feet to navigate such environments, but motion planning for the robot presents significant challenges. Gaited locomotion planners are not suitable due to the complex manoeuvres required and hence non-gaited full-body motion planning is required. We present a planning approach which uses a pre-computed Contact Dynamic Roadmap (CDRM) data structure to allow for rapid foothold configuration evaluation, enabling online non-gaited motion planning in complex 3D environments.

We use a hierarchical planning approach - a Rapidly exploring Random Tree (RRT) [2] composed of robot body poses is used to explore the environment. Once a body pose has been sampled, we use a CDRM to rapidly evaluate foothold configurations. The CDRM is an extension of Dynamic Roadmaps (DRM) [3] which pre-computes a mapping from the configuration space of a leg to its workspace. The CDRM enhances the DRM by also including a mapping of foot-tip contact position information. During online planning, when the environment is known, this mapping is used to evaluate many candidate foothold configurations for each leg with a single collision check. This allows rapidly identifying valid footholds in a complex environment, which is the main planning bottleneck. Individual valid foothold configurations for each leg are then combined together to create full-body states.

We have validated the planner in simulation, with promising initial results. We evaluated both individual features such as steps and gaps, as well as complex scenarios such as the 3D truss shown in Fig. 1c. For the 3D truss scenario, the planning time was 77s with an 80% success rate. Across all scenarios, the motion plans fully exploited the range of the robot's reachability before failure rates became high. We are currently implementing the planning algorithm on the quadruped platform shown in Fig. 1b.

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In-situ Terrain Estimation and Stability Analysis for Bipedal Humanoid Robots

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Space exploration robotics has been a vibrant and active research area ever since the beginning of the human spaceflight program. A variety of satellites, probes, landers, and rovers have explored various celestial bodies within our solar system. Future robotic exploration missions though will require advances in specific capabilities to enable human exploration to reach farther. To successfully support crewed exploration on Mars, multiple launches spread over a period of years will be required to predeploy the necessary equipment, habitats, and supplies. These predeployed assets will need to be maintained over the years to ensure their availability and functionality for the crew when they arrive to complete their scientific objectives. Because the predeployed assets are designed to be used by astronauts, a robot in humanoid form is most likely to be able to complete generic maintenance and support tasks that arise during the course of the mission.

The Space Robotics Challenge is a NASA Centennial Challenge in which teams will compete in a virtual challenge first, demonstrating competency with mobility, manipulation, and perception tasks on a virtual Valkyrie robot. Robust bipedal locomotion in unstructured environments is needed to enable the completion the SRC tasks, in the short term, and similar tasks in future robotic missions to Mars. At the current state of the art, bipedal humanoid robot locomotion is largely successful in well-known, structured environments with flat, non-deformable footholds. However by its nature, exploration domains are full of unstructured and uncertain environments and can include areas with deformable terrains, such as sand or dirt. Utilizing current approaches and methods, humanoid robots lack the robustness to navigate such a domain as demonstrated by the spectacular falls of many robots at the DARPA Robotics Challenge Finals on the sandy terrain.

The work we present focuses on classification of the ground type which can be leveraged to improve the stability of humanoid robots on deformable terrain. One way to accomplish this is by estimating the ground properties using proprioceptive sensor feedback from the foot of the robot. We present our experimental procedures in detail and data with NASA's humanoid robot, Valkyrie, performing a set of pre-specified motions on different terrains, including concrete, foam, mulch, rubber and sand. A relative stiffness for each terrain is modelled based on the experimental data resulting in the prediction of the ground type. We will also present our ongoing work on stability analysis of different step size selection on deformable terrains. A comparison of COM trajectory projection on support polygon of Valkyrie walking on solid ground and deformable terrains with different step size will be presented. From this comparison, it is worth noting that an uncentered COM position may cause deformation of support polygon, which should be avoided. We will present our approaching of adjusting the COM position by selecting proper step size and transit time on deformable terrain. We expect the experimental data gathered in our laboratory setting can be used to design and improve the controllers for traversing different types of terrain.

By analyzing the video of Valkyrie falling on foam, we found one possible reason why COM deviate far away from the center of support polygon with longer step size. When Valkyrie walks on deformable terrain, she took the sunken lowered surface as the ground, while the robot's swing foot will get in touch with un-deformed higher surface earlier in actual. Since Valkyrie plans a farther COM trajectory based on the lower ground, a deviation happens. Experiments are needed to verify this assumption.

An Alternative Derivation of the Linear Inverted Pendulum Model

Oliver Urbann and Ingmar Schwarz

The Linear Inverted Pendulum model is a well-known and popular approach for biped gait planing as it provides the relation between the Zero Moment Point (ZMP) based on a single center of mass (CoM). It is linear and can therefore be applied to various approaches to generate a motion of the CoM given a desired ZMP trajectory. However, for beginners in research or in education the derivation as presented in [1] can be confusing and presents many details that are not required.

Here we intend to present two derivations. The first is a intuitive approach to the ZMP by explaining the concept using a beam balance. In the following we derive the ZMP of the Linear Inverted Pendulum model as presented in [1].

Zero Moment Point of a Multi-Body System

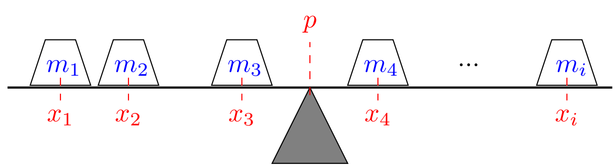

Figure 1: Beam balance with multiple masses.

The ZMP as defined by Vukobratović [2] is a result of torques and forces due to accelerations which includes gravity. In a simplified manner we now assume that all accelerations are caused by gravity to explain the concept of the ZMP utilizing a beam balance as depicted in Fig. 1. We search for the coordinate[1] of the Zero Moment Point p where the sum of all torques is 0. If our base supports the beam at this point, the beam is stable. For all $k \in \{1, \dots, i\}$ the force is $f_k = m_k \cdot g$, where g is the gravity. Thus, the base must support the beam with a total force of $F = \sum f_k$ at point p leading to the equation of all torques acting in this system:

$$F \cdot p = \sum (f_k \cdot x_k) \Leftrightarrow p = \frac{\sum (f_k \cdot x_k)}{F}$$

Zero Moment Point of the Linear Inverted Pendulum Model

We now consider the ZMP to be at $p = 0$. Comparably to the derivation above the sum of all torques in this system must be zero at $p = 0$: It follows that $\tau_1 = \tau_2$. Due to gravity we have $\tau_1 = m \cdot g \cdot x$, where m is the mass, x the one-dimensional position of the mass and g gravity. To realize τ_2 the system must be accelerated and it follows $\tau_2 = m \cdot \ddot{x} \cdot z_h$ where z_h must be constant to neglect dynamics of changing height. Rearranging leads to:

$$\begin{aligned} \tau_1 &= \tau_2 && \Leftrightarrow \\ m \cdot g \cdot x &= m \cdot \ddot{x} \cdot z_h && \Leftrightarrow \\ 0 &= x - \frac{z_h}{g} \ddot{x} \end{aligned}$$

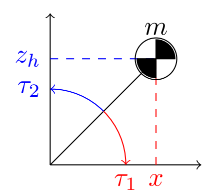

Figure 2: Linear Inverted Pendulum Model

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[1] Please note that the ZMP must be on the floor and is thus one-dimensional in this planar example.

Multi-sensor Perception for Robust Localization of Dynamic Robots

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Abstract

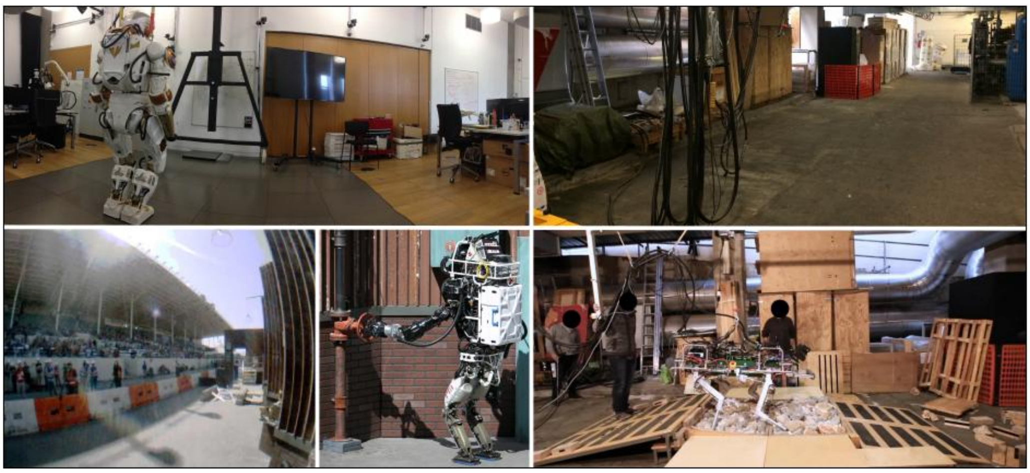
State estimation strategies for dynamic robots are typically based on inertial sensing and leg kinematics, and are affected by continuous drift. Laser measurements can be used to compensate for this drift via 3D scene registration.

In this work, we present a system for robust localization of floating-base robots. The approach fuses inertial, kinematic, stereo vision and laser signal sources to achieve robust and accurate continuous estimation of the robots base link states (pose and velocity), in the presence of challenges such as limited field of view, uneven terrains and crowds of people in the environment, as well as disturbances such as slips and missteps. Our solution builds upon a modular inertial-driven Extended Kalman Filter based state estimator, with additional inputs from stereo visual odometry and laser registration. We show that the simultaneous use of both stereo vision and laser helps combat operational issues which occur in real applications.

The first contribution is a laser-based localization system capable of overlap-based auto-tuning [2]. As part of the registration module, the outlier rejection filter is automatically tuned at run-time to allow alignment to a fixed reference cloud, in conditions of non-uniform overlap. The reference cloud is updated rarely, when the overlap drops to negligible percentages. The non-incremental registration strategy allows the system to avoid accumulated errors and satisfy exacting accuracy and robustness requirements.

Secondly, to the best of our knowledge, this work is the first to discuss the complexity of consistent estimation of pose and velocity states, as well as the fusion of multiple exteroceptive signal sources at largely different frequencies and latencies, in a manner which is acceptable for a quadrupeds feedback controller [1].

Extensive experimental evaluations have been carried out in closed loop control on the NASA Valkyrie humanoid robot and the IIT quadruped HyQ, during exploration of a variety of semi-structured environments. Further experiments have been run on the Boston Dynamics humanoid Atlas, using a dataset collected during the DARPA Robotics Challenge Finals. The system demonstrated continuously accurate localization and drift per distance travelled below 1 cm/m on highly dynamic gaits and speed up to 0.5 m/s.



The NASA humanoid robot Valkyrie, operating in a laboratory (top left). The Boston Dynamics humanoid Atlas during the DARPA Robotics Challenge finals (bottom left, photo credits: MIT team). The IIT quadruped HyQ operating on a challenging terrain (right).

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State Estimation in the Loop for Accurate Base Pose and Velocity Tracking of Dynamic Legged Robots

Marco Camurri*, Maurice Fallon†, Victor Barasuol*, Darwin G. Caldwell*, and Claudio Semini*

***Abstract*— In this work, we present the fusion of proprioceptive and exteroceptive sensing to achieve accurate base pose and velocity tracking of the 85 kg quadruped robot HyQ. By means of a modular Extended Kalman Filter (EKF) framework, we fuse (at high frequency) the information from an Inertial Measurement Unit (IMU) and a probabilistic Leg Odometry (LO) module to achieve smooth and accurate velocity estimation. For accurate pose estimation, we incorporate low-frequency pose updates to the filter through a scan matcher module. These two states (pose and velocity) are then tightly coupled with the trunk controller, in order to keep the robot in place while trotting, despite considerable disturbances induced by a human operator.**

I. Introduction

Legged robots are expected to outperform wheeled and tracked systems when they come to navigate in unstructured, uneven, and rough terrains. However, legged robots are characterized by higher mechanical complexity and require more sophisticated control strategies to navigate without falling, slipping or getting stuck.

The difficulty in the development of autonomous legged navigation lies in the close relationship between perception and locomotion. On one hand, the robot has to elaborate a myriad of signals (coming from itself and the environment) and combine them into useful information. On the other hand, it has to use this information to safely navigate in the environment. Furthermore, these two processes have to be concurrently executed onboard and in real-time.

In this work, we present a modular state estimation framework which fuses proprioceptive and exteroceptive sensing for accurate pose and velocity estimation of the robot. The estimate is then tightly coupled with the Reactive Controller Framework (RCF) [1] to maintain the robot's base upright and on a target location, despite the strong disturbances applied by a human operator. Both quantitative and qualitative results demonstrate the good performance system on the dynamic legged robot HyQ [2].

II. Proprioceptive State Estimation

In our previous work [3], we presented a novel proprioceptive state estimation method for dynamic quadruped robots without contact sensors. The method is based on an Extended Kalman Filter (EKF) driven by an inertial process model, as described in [4], [5]. The Leg Odometry (LO) module of the filter have been designed to: classify the contact forces in order to detect the useful velocity contributions from the legs in contact; and estimate the covariance taking into account impact forces. We build upon the aforementioned framework by integrating pose updates from LiDAR device, as explained in the following section.

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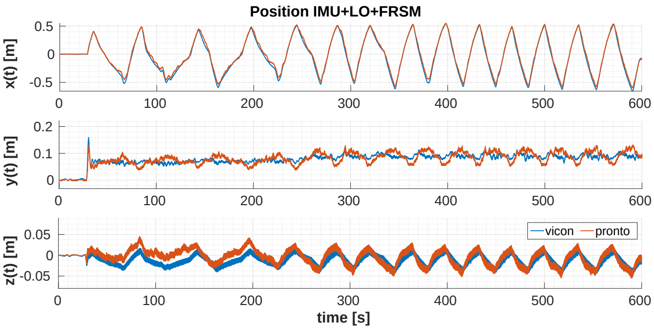

Fig. 1. Position of IMU + LO + FRSM modules (fused with *Pronto*, the EKF introduced in [5] and used in [3]) against Vicon.

III. Fast and Robust Scan Matcher

The Fast and Robust Scan Matcher (FRSM) is an Inertial-LiDAR based localization library introduced in [6] for autonomous quadrotor flight in GPS-denied environments. The FRSM algorithm solves the registration problem in the 2D domain with a map-based probabilistic approach rather than frame-to-frame iterative optimization. This guarantees robustness against errors due to slightly non-horizontal motion, as proved by the authors in [6]. The output of the library is used as position and yaw updates of the filter, which fuses them together with inertial information and LO. To this end, we mounted a Hokuyo URG-04LX horizontally on the robot's trunk.

IV. Experimental Results

A. *Pose Estimation Performance*

Fig. 1 shows the position performance on a trotting motion. The FRSM is able to eliminate the drift in position, which would make the position control on the robot's base unreliable.

B. *In-the-Loop Control Performance*

Fig. 2 shows some screenshots from the experiment. The robot is trotting in place and commanded to keep a zero position (green edge beside the treadmill). After a series

Fig. 2. Push recovery with state estimation in the loop. The robot was commanded to trot in place and keep its position. After several pushes from the operator, the robot recovered its position along the green line of the treadmill. The ability to recover its position in a constrained space using the state estimation in the loop demonstrates the reliability and robustness of the filter.

of disturbances from the operator, the robot returns to the zero position with no drift. The experiment demonstrates qualitatively the robustness and reliability of the estimator. Note that, by the design of the push recovery algorithm [1], both position and velocity estimates are used at the same time. This demonstrates how the filter is gracefully fusing different sensor inputs into a smooth and accurate signal.

V. Conclusion

We have presented a modular framework to fuse proprioceptive and exteroceptive sensing in order to achieve highly accurate pose and velocity estimates of the dynamic quadruped robot HyQ. The inertial information and the LO presented in [3] contributes to smooth and accurate velocity estimation, required for effective disturbance rejection during dynamic motions. The contribution of the FRSM module contributes to maintain the base position, as demonstrated on live experiments on the robot.

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Robust bipedal Locomotion Control based on Model Predictive Control and Divergent Component of Motion

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Abstract: In order to realize the dream of employing humanoid robots in our real world, developing a unified, robust and versatile framework for bipedal locomotion control is essential. To take a step toward this goal, we develop a framework for balance recovery of a biped robot based on Model predictive Control(MPC) and Divergent Component of Motion(DCM). We employ a single MPC which uses a combination of Center of Pressure (CoP) manipulation, step adjustment, and Centroidal Moment Pivot (CMP) modulation to design a robust locomotion controller. Furthermore, we exploit the concept of time-varying DCM to generalize our walking controller for walking on uneven surfaces. Using our scheme, a robust walking controller is designed which can be implemented on robots with different control authorities, for walking on various environments, e.g. uneven terrains or surfaces with a very limited feasible area for stepping.

Keywords: Model Predictive Control, Divergent Component of Motion, Robust Bipedal Locomotion Control, Push Recovery

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Whole-body walking motion generation with optimal control

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Walking is still an open challenging problem for humanoid robots, where reduced models such as the inverted pendulum, the table-cart and the spring loaded inverted pendulum are often preferred due to the faster computations times and easier dynamics. Despite their popularity, it is known that such models do not allow to exploit the whole-body dynamics of the robot, resulting in walking motions where the upper body does not perform any motion.

In order to take into account the whole-body dynamics, we use optimal control to generate whole-body walking motions. In particular, we use the model of the humanoid robot HeiCub, which is a reduced version of the humanoid robot iCub [1] without arms and head and with legs designed for locmotion tasks. The HeiCub is located in Heidelberg and was built as part of the European Project KoroiBot [2] to perform walking experiments. In a previous work we analysed the walking capabilities of the robot in several environments by means of a table-cart based pattern generator [3] and gathered information about the capabilities and limitations of the robot that have to be taken into account in optimal control problems under the form of constraints, parameters and objectives.

Walking is a multiphase motion, where a set of phases can be identified in terms of different sets of contacts between the feet and the environment. Therefore we formulate the problem as a multiphase optimal control problem. In particular, we look at straight level ground walking, where the phases of a humanoid robot with rigid flat feet, such as HeiCub, can be identified as in Fig. 1. The first and final phases are the initialisation and ending phases, while the phases in between represent the cyclic step which can be described as periodic. Each phase is described with a different set of differential equations according to the contacs, which are assumed to be rigid. The impacs are assumed to be inelastic and instantaneous, therefore they are described as phases with zero time, where the generalized velocities change after the impact.

We set as controls of the optimal control problem the joint torques $\mathbf{u}(t) = \tau(t)$ and as states the generalized positions and velocities of the robot, such that the differential states are $\dot{\mathbf{x}}(t) = [\dot{\mathbf{q}}(t)\ \ddot{\mathbf{q}}(t)]^T$, which right hand side is computed using forward dynamics by using the whole-body dynamics of the robot. The physical limitations of the robot, such as joints range, velocities, torques are imposed as boundary constraints. Other constraints include the contact sets, collision avoidance, stability (e.g. as ZMP) and periodicity, where periodicity is imposed on the cyclic step, such that it can be

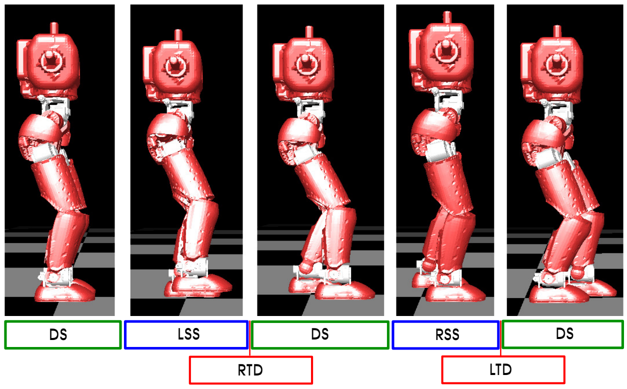

Figure 1: Walking phases for flat feet humanoid robots, from initialisation to end steps. Where R stands for right foot, L for left foot, D for double support and S for single support. TD stands for touch down, i.e. impact.

repeated in sequence for the execution on the robot. The step length is represented as parameter. The objective function includes the minimization of mechanical work, maximization of walking velocity and step length, which are combined together as a weighted function.

The whole-body motion is then generated given an initial guess, taking into account the whole-body dynamics and constraints for the given objective, by simultaneously optimizing the states, controls, free parameters and time, which can be left free or fixed to desired values for each phase. The problem is solved using a direct multiple shooting method offline, due to the complexity of the computations. The formulation is here carried out for level ground walkin but can be adapted to any walking environment given proper contact sets.

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