Outline

1. Introduction
2. Relevant projects
3. Research proposal
4. Expected results

Introduction

Octavio A. Villarreal Magaña

- MSc. Mechanical Engineering, track Control Engineering (TUDelft, The Netherlands)
  - Control Methods for Robotics
  - Robust Control
- BSc. Mechatronic Engineering (UNAM, Mexico)
  - Systems and Control
  - Robotics

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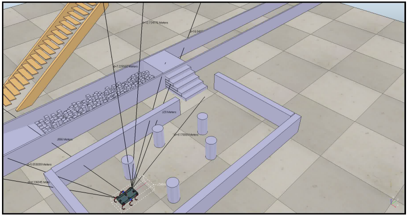
Locomotion Control of Zebro

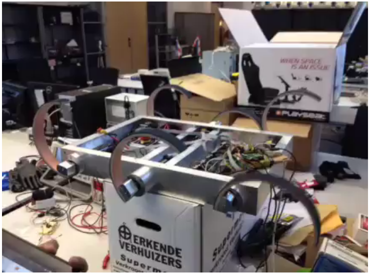
- Course project
- Locomotion control of six-legged robot
- Use of max-plus algebra[1]
- Traversing unstructured terrain
- Safe gait switching



[1] G. A. D. Lopes, T. J. J. V. D. Boom, B. D. Schutter, and R Babu (2010). "Modeling and control of legged locomotion via switching max-plus systems". In: *Proceedings of the 10th International Workshop on Discrete Event Systems (WODES 2010)*, 6 pp.

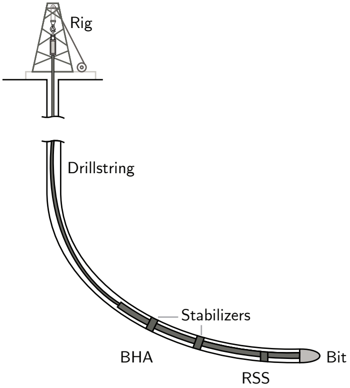
Implementation in real robot

- Commissioned by dutch artist
- Max-plus algebra for reference generation
- Independent controller for each leg
- Construction of the robot
- Implementation using ROS
- Simple obstacle avoidance



Robust output-feedback control of 3D directional drilling systems

- MSc Thesis
- In collaboration with the University of Minnesota
- Complex dynamics (Delay Differential Equations)
- Observer design to only use local measurements
- Robust against parameter uncertainty

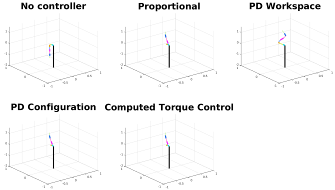


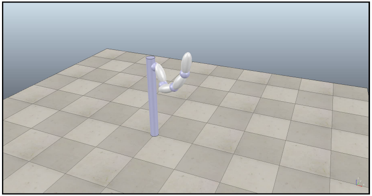
Control of robotic arm

- Control Methods for Robotics course assignment

- Four rotational joints

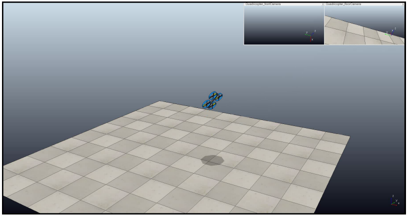
- Different control algorithms (Workspace and configuration space control)





Nonlinear geometric control of quadcopter

- Control Methods for Robotics course assignment
- Workspace and orientation nonlinear control
- Capable of performing aggresive maneuvers[2]



[2] T. Lee, M. Leok, and N. Harris McClamroch (2010). "Control of Complex Maneuvers for a Quadrotor UAV using Geometric Methods on SE(3)". In: *ArXiv e-prints*. arXiv: 1003.2005 [math.OC]

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Objective of max-plus algebra in locomotion

"Obtain synchronized time references for each of the leg's lift-off times (moment when a leg leaves the ground) and touch-down times (moment when a leg touches the ground) in a systematic way".

Definition of max-plus algebra

"Tropical" algebra defined by:

$$(\Re_{max}, \oplus, \otimes, \varepsilon, e)$$

where:

$$\begin{aligned} \Re_{max} &:= \Re \cup \{-\infty\}, \\ x \oplus y &:= max(x, y), \\ x \otimes y &:= x + y, \\ \varepsilon &:= -\infty, \\ e &:= 0. \end{aligned}$$

Definition of max-plus algebra

Extension to matrices:

$$(\Re_{max}^{n\times m}, \oplus, \otimes, \mathcal{E}, E)$$

with:

$$[A \oplus B]_{ij} = a_{ij} \oplus b_{ij} := \max(a_{ij}, b_{ij}),$$

$$[A \otimes C]_{ij} = \bigoplus_{k=1}^{m} a_{ik} \otimes c_{kj} := \max_{k=1,\ldots,m}(a_{ik} + c_{kj}),$$

Absorbing and identity element:

$$[\mathcal{E}]_{ij} = \varepsilon,$$

$$[E]_{ij} = \begin{cases} e, & \text{if } i = j \\ \varepsilon, & \text{otherwise.} \end{cases}$$

Powers:

$$D^{\otimes k} := D \otimes D \otimes \ldots \otimes D.$$

Gait generation using max-plus algebra

Gait Parameters[3]:

i	Leg index.
$t_i(k)$	Touchdown time of leg.
$l_i(k)$	Lift-off time.
τ	Current time instant.
τ_f	Flight time.
τ_g	Ground time.
τ_Δ	Double stance time (adjustable).

[3] G. A. D. Lopes, T. J. J. V. D. Boom, B. D. Schutter, and R Babu (2010). "Modeling and control of legged locomotion via switching max-plus systems". In: *Proceedings of the 10th International Workshop on Discrete Event Systems (WODES 2010)*, 6 pp.

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Gait generation using max-plus algebra

Gait cycle description for a biped:

$$
\begin{aligned}
t_1(k+1) &= l_1(k+1) + \tau_f \\
l_1(k+1) &= t_1(k) + \tau_g \\
t_2(k+1) &= l_2(k+1) + \tau_f \\
l_2(k+1) &= t_2(k) + \tau_g
\end{aligned}
$$

Synchronization:

$$
\begin{aligned}
t_1(k+1) &= l_1(k+1) + \tau_f \\
l_1(k+1) &= \max(t_1(k) + \tau_g, t_2(k) + \tau_\Delta) \\
t_2(k+1) &= l_2(k+1) + \tau_f \\
l_2(k+1) &= \max(t_2(k) + \tau_g, t_1(k+1) + \tau_\Delta)
\end{aligned}
$$

Gait generation using max-plus algebra

Described as a max-plus linear system:

$$\underbrace{\begin{bmatrix} t_1(k+1) \\ t_2(k+1) \\ l_1(k+1) \\ l_2(k+1) \end{bmatrix}}_{x(k+1)} = \underbrace{\begin{bmatrix} \tau_f \otimes \tau_g & \tau_f \otimes \tau_\Delta & \varepsilon & \varepsilon \\ \tau_f^{\otimes 2} \otimes \tau_g \otimes \tau_\Delta & (\tau_f \otimes \tau_\Delta)^{\otimes 2} & \varepsilon & \varepsilon \\ \tau_g & \tau_\Delta & \varepsilon & \varepsilon \\ \tau_f \otimes \tau_g \otimes \tau_\Delta & \tau_f \otimes \tau_\Delta^{\otimes 2} & \varepsilon & \varepsilon \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} t_1(k) \\ t_2(k) \\ l_1(k) \\ l_2(k) \end{bmatrix}}_{x(k)}$$

Gait definition:

$$\mathcal{G}_{walk} = \{1\} \prec \{2\}$$
$$\mathcal{G}_{hop} = \{1, 2\}$$

Advantages

- Systematic gait generation
- Number of legs does not increase complexity greatly
- Safe gait switching [4]
- Total cycle-time, steady-state and transient behavior analysis by studying properties of A matrix

[4] G. A. D. Lopes, R. Babuška, B. De Schutter, and A. J. J. Van Den Boom (2009). "Switching max-plus models for legged locomotion". In: *2009 IEEE International Conference on Robotics and Biomimetics, ROBIO 2009* 19, pp. 221–226. DOI: 10.1109/ROBIO.2009.5420626

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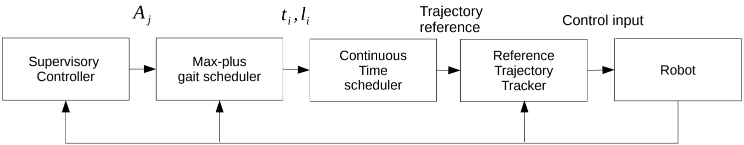
Locomotion control of walking robots



Locomotion control of walking robots

- Supervisory control : Defines A_j matrix (τ_g, τ_f, τ_Δ,etc.)
  - Uses sensor information
- Gait scheduler: Defines lift-off and touch-down times for each leg (final and initial times for trajectory)
- Continuous time scheduler: Defines trajectory for each of the legs based on scheduled times
  - For example, an ellipsoidal trajectory
- Reference trajectory tracker: Follows the trajectory defined
  - e.g. workspace computed torque control

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- Systematic method to generate gaits
- Methodology could provide safe gait switching
- Could be applied to several topologies of multi-legged robots
- Could provide robustness against unstructured scenarios