CPS
-- some thoughts from a robotics perspective --

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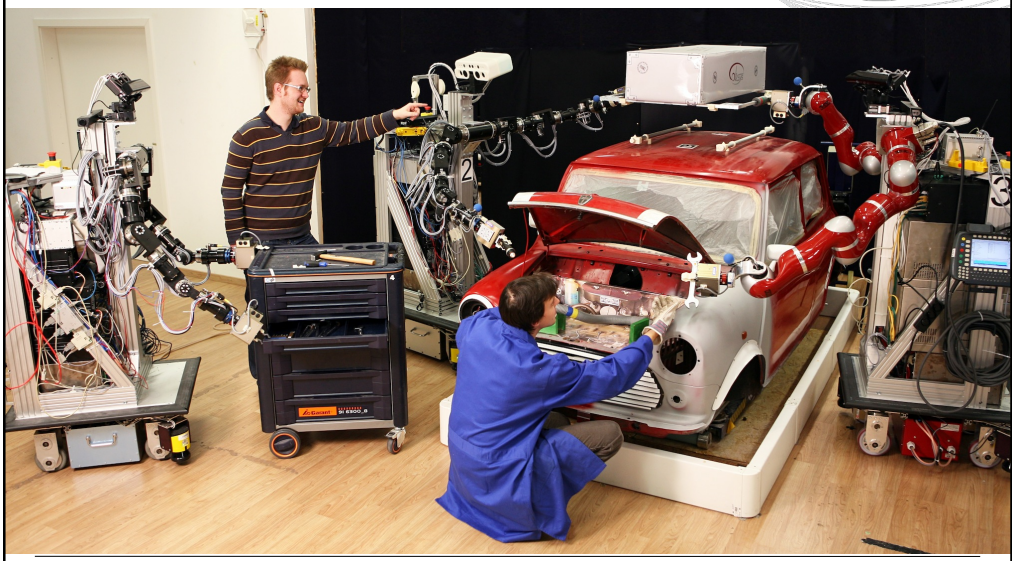
Robotics@TUM

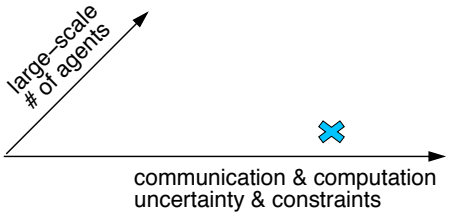


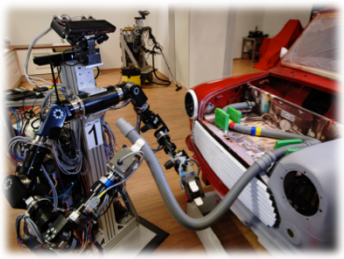
Example 1: Networked visual servoing

Facts

- cheap sensing: ~40MB/s raw 3D data from 1 sensor for 150USD!!
- typically requires computational expensive pre-processing
- mobility: limited local computational power, but access to cloud?
- mobility: wireless communication

→ **Serious communication & computation constraints**

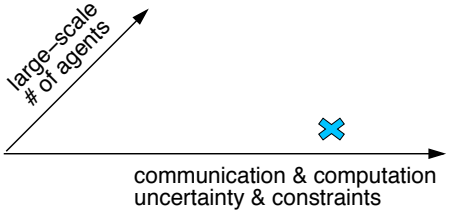


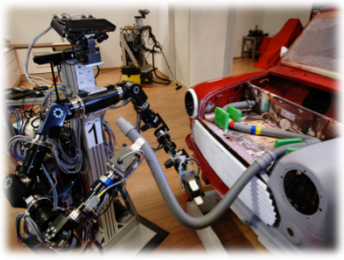


Example 1: Networked visual servoing

Challenges

- Control architecture: where to compute and what to communicate?
- Performance trade-offs: local/remote computation given communication
- Fast or accurate: relationship between control performance and computational complexity?
- Joint control of resource and system: comp & comm models
- Plug & play sensing, computation, and actuation → structural adaptation & reconfiguration

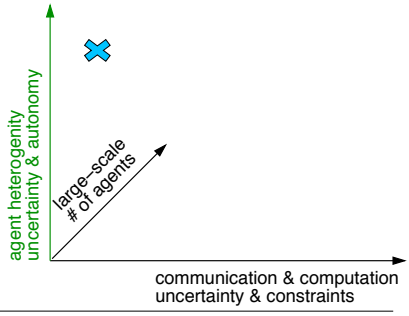




Example 2: Robot teams

Additional dimension for CPS

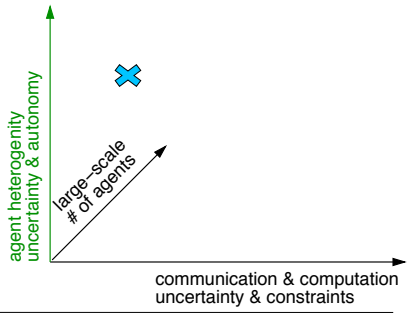
- Few but largely autonomous agents with complex decision making dynamics -> model uncertainty and partial information
- Distributed heterogeneous sensing and computation resources



Example 2: Robot teams

Challenges:

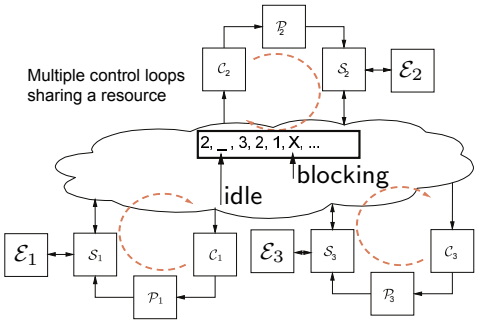
- Distributed control under significant uncertainty and low model trust
- Advanced negotiation schemes for sharing resources and control across autonomous robots
- Reconfiguration, structural adaptation, etc.

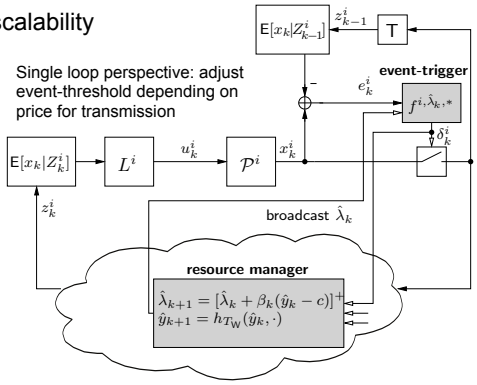


[Medina et al. ICRA2012 "Risk-sensitive control in haptic assistance"]

Optimal control & resource sharing

- Multiple control loops sharing a resource
- Optimal event-triggered control: extended LQR + average global rate constraint
- Bi-level design: local optimal control & event-trigger, resource allocation via pricing
- Asymptotic optimality
- Better than time-triggered: efficiency and scalability





Summary

- Control/communication/computation architecture: where and what?
- Joint (cooperative) control of resources and “plant”
- Distributed control with uncertain models (tradeoffs between privacy and performance)
- Reconfiguration and structural adaptation

Selected publications

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A. Molin, S. Hirche, *Adaptive Event-triggered Control over a Shared Network*, Proceedings of the 51st IEEE Conference on Decision and Control (CDC) , 2012 , *accepted.*

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S. Hirche and M. Buss, *Human-oriented control for haptic teleoperation*, Proceedings of the IEEE, vol. 99, no. 1, pp. 1–25, 2012.

A. Mörtl, M. Lawitzky, A. Kucukyilmaz, M. Sezgin, C. Basdogan, S. Hirche, *The Role of Roles: Physical Cooperation between Humans and Robots* , International Journal of Robotics Research , (2012), to appear

E. Steinbach, S. Hirche, M. Ernst, F. Brandi, R. Chaudhari, J. Kammerl, and I. Vittorias, "Haptic communications," Proceedings of the IEEE, vol. 100, no. 4, pp. 937– 956, 2012.

J. Qin, C. Yu , and S. Hirche, "Stationary consensus of asynchronous discrete-time second-order multi-agent systems under switching topology," IEEE Trans. on Industrial Electronics, 2012, to appear.

A. Molin, S. Hirche, *On the Optimal Design of Decentralized Event-triggered Controllers for Large-scale Systems with Contention-based Communication*, Proceedings of the IEEE International Conference on Decision and Control (CDC'11), 2011, p. 4710–4716

J. Liu, A. Benigni, D. Obradovic, S. Hirche, A. Monti, *State Estimation and Branch Current Learning Using Independent Local Kalman Filter With Virtual Disturbance Model* , IEEE Trans. on Instrumentation an Measurement , **60** (2011) , no. 9 , 3026-3034

E. Steinbach, S. Hirche, J. Kammerl, I. Vittorias, R. Chaudhari, *Haptic Data Compression and Communication*, IEEE Signal Processing Magazine, **28** (2011), no. 1 , 87-96 .

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H. Wu, L. Lou, C.-C. Chen, S. Hirche, K. Kühnlenz, *Performance-Oriented Networked Visual Servo Control with Sending Rate Scheduling* , Proceedings of the IEEE International Conference on Robotics and Automation (ICRA) , 2011 , p. 6180-6185

H. Wu, C.-C. Chen, J. Feng, K. Kühnlenz, S. Hirche, *A Switching Control Law for a Networked Visual Servo Control System* , Proc. of the IEEE International Conference on Robotics and Automation (ICRA), Anchorage, Alaska, USA , 2010 , p. 5556 - 5563

H. Wu, L. Lou, C.-C. Chen, K. Kühnlenz, S. Hirche, *Distributed Computation and Data Scheduling for Networked Visual Servo Control Systems*, Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) , 2010 , p. 6216 - 6221 .

H. Wu, L. Lou, C.-C. Chen, S. Hirche, K. Kühnlenz, *A Framework of Networked Visual Servo Control System with Distributed Computation* , Proc. of the International Conference on Control, Automation, Robotics and Vision (ICARCV) , 2010 , p. 1466 - 1471

A. Molin, S. Hirche, *Optimal Event-triggered Control under Costly Observations*, Proceedings of the 19th International Symposium on Mathematical Theory of Networks and Systems (MTNS'10), Budapest, Hungary, 2010, p. 2203-2208 .

A. Molin, S. Hirche, *Suboptimal Event-based Control of Linear Systems over Lossy Channels* , 2nd IFAC Workshop on Estimation and Control of Networked Systems (NecSys'10), Annecy, France, 2010, p. 55-60 .

A. Molin, S. Hirche , *Structural Characterization of Optimal Event-based Controllers for Linear Stochastic Systems* , Proceedings of the IEEE International Conference on Decision and Control (CDC'10), Atlanta, USA , 2010, p. 3227-3233 .

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S. Hirche, T. Matiakis, M. Buss, *A Distributed Controller Approach for Delay-Independent Stability of Networked Control Systems*, automatica, **45** (2009), no. 8, 1828-1836 .