Progress Summary

NSF award CNS-0932423: "Real-time, Simulation-based Planning and Asynchronous Coordination for Cyber-Physical Systems"

PI: Kostas Bekris

Intellectual Merit

The project aims to develop abstractions and general solutions for autonomous planning and coordination in networks of cyber-physical systems. In particular, the following challenges were identified in order to achieve the above objective:

a. Develop abstractions and sampling-based motion planning algorithms that can be appropriately integrated with simulation tools to utilize their predictive capabilities without requiring detailed or well-behaved mathematical models.

Progress:

We have developed methods for improving the performance of sampling-based algorithms, which do not depend on the knowledge of a specific model and which can operate given a simulation tool to model the underlying system [7,8]. In the meanwhile, an important development in the motion planning community has been the proposition of motion planners that provide asymptotical optimality guarantees. These methods, however, have significant computational requirements. We have proposed a series of algorithms that provide asymptotic near-optimality guarantees and which require significantly reduced computational resources [13,14,15,3].

b. Address safety issues that arise due to the presence of real-time constraints, such as operating in dynamic and partially-observable environments, and especially given asynchronous coordination protocols between multiple agents towards providing safety guarantees.

Progress:

We have provided a report that summarizes the state-of-the-art in addressing safety issues in the context of real-time planning [2]. This line of work has been extended to the case of multiple coordinating vehicles that utilize asynchronous communication in order to navigate in a common environment, while achieving safety guarantees [1] [4]. We have also developed methods for the decentralized, collision-free coordination of multiple agents, which involves either no or very limited communication [5][6].

c. Study how inconsistent estimation and partial knowledge among multiple agents of a team affects distributed decision-making and work towards applications in CPS domains.

Progress:

We have developed methods for computing paths for multiple agents in a decentralized, localized manner on discrete representations by utilizing static sensors, which are able to communicate with the agents [9][12]. The focus of this work has been on transportation scenarios, which is one of the CPS application domains for this project. A drawback of this type of methods is the lack of

completeness guarantees. This motivated the development of methods with completeness guarantees for a broad range of multi-agent path planning instances on discrete representations, which have polynomial complexity [10][11][16]. This project has also led into the specification of an open-access, decentralized architecture for the control of the power network [17], as well as the development of closed-loop methods for the control of medical devices [18].

Broader Impact

In relation to the intellectual merit, this project also aims to achieve the following:

a. Develop and distribute open-source planning and control software which provides appropriate abstraction tools so as to be applied to a variety of CPS applications;

Progress:

An initial version of the proposed open-source planning and control software has been completed and a related paper has been submitted to a conference, which will illustrate the capabilities of the platform [19]. Upon acceptance of the paper, the software package will be released to the community.

b. Integration of research outcomes in the educational material of courses taught and creation of educational material relevant to the CPS community;

Progress:

Results from the conducted research have been integrated in the courses "Planning Algorithms", "Multi-Agent Systems" and "Optimal Control and Reinforcement Learning" that the PI has taught over the last three years at the University of Nevada, Reno.

c. Organization of meetings and sessions on physically-grounded agents;

Progress:

The PI has been active in organizing meetings related to the theme and the objectives of the project. In particular the PI has been co-chair in the following related workshops and special sessions over the lifetime of the project:

- The "1st International Multiagent Pathfinding Workshop" colocated with the AAAI Conference on Artificial Intelligence (AAAI), 22 July 2012, Toronto, Ontario, Canada (together with Dr. Nathan Sturtevant, U. of Denver and Dr. Ariel Felner, Ben Gurion University, Israel)
- Workshop on "Open Problems and Challenges of Motion Planning" IEEE International Conference on Intelligent Robots and Systems (IROS), 30 Sept. 2011, San Francisco, CA (together with Dr. Tim Bretl, UIUC and Prof. Dan Halperin, Tel-Aviv University, Israel)
- Symposium on the "Foundations and Prospects of Sampling-based Motion Planning" Special Symposium celebrating the 50 years of Robotics Research IEEE International Conference on Intelligent Robots and Systems (IROS), 27 Sept. 2011, San Francisco, CA (Invited to organize - together with Prof. Steve LaValle, UIUC)

- Workshop on "Guaranteeing Motion Safety for Robots" Robotics: Science and Systems (RSS), 27 June 2011, Los Angeles, California. (together with Dr. Thierry Fraichard - INRIA, France and Dr. Jur van den Berg -UNC Chapel Hill)
- Workshop on "Motion Planning: From Theory to Practice" Robotics: Science and Systems (RSS), 27 June 2010, Zaragoza, Spain (together with Ron Alterovitz - UNC Chapel Hill, Juan Cortes - INRIA, France and Kris Hauser, U. of Indiana)

d. Involvement, training and mentoring of undergraduate and graduate students, especially women, in research activities related to cyber-physical systems;

Progress:

Through the support provided by this grant the PI had the opportunity to involve multiple graduate and undergraduate students in research activities related to cyber-physical systems. In particular, eight undergraduate students were involved with this project (Andrew Dobson, Ryan Luna, Alexis Oyama, Zakary Littlefield, Ethan Pang, Qandeel Sajid, Justin Cardoza, Jared Rhizor). Three of these students decided to continue into graduate school. During the lifetime of the award there have been seven graduate students involved with this project (Yanbo Li, Ryan Luna, Andrew Dobson, James Marble, Zakary Littlefield, Athanasios Krontiris, Andrew Kimmel). Note that this list includes a female undergraduate student (Ms. Qandeel Sajid) and one student from an under-represented group in STEM (Mr. Ryan Luna).

e. Attraction of K-12 students in STEM and cooperation with high schools and interaction with underrepresented groups;

Progress:

The PI has been active in STEM-related events that involve K-12 students, such as visits to research labs and talks to high-schools. In particular, the PI has been involved in the following events:

- Lectures for the Public
  - Robotics Lecture Series (organizing and speaking) - Osher Lifelong Learning Institute - UNR. ◦ 16 October 2011 and 31 October 2011.
- Summer School for K-12 students
  - Participating in the summer school on transportation research: July 2011 at UNR.
- Visits by High-Schools to the Robotics Lab
  - 25 March 2011, Davidson Academy of Nevada Nevada Bound
- Lab tours and presentations to K-12 students visiting the UNR campus
  - 20 February 2009, 29 January 2010, 3 December 2010
- UNR STEM Open House
  - 18 November 2010
- High-School Visits and Lectures
  - 3 November 2010, Davidson Academy of Nevada
- Judge at the Intel International Science & Engineering Fair (Intel ISEF)
  - Reno, Nevada, May 10-16 2009.

Related Papers

[1] Bekris K E., Grady D K., Moll M., Kavraki L E., "Safe Distributed Motion Coordination for Second-Order Systems With Different Planning Cycles", International Journal of Robotics Research (IJRR), vol. 31, no. 2, February 2012.

[2] Bekris K E., "Avoiding Inevitable Collision States: Safety and Computational Efficiency in Replanning with Sampling-based Algorithms", Workshop on "Guaranteeing Safe Navigation in Dynamic Environments", International Conference on Robotics and Automation (ICRA-10), Anchorage, AK, May 2010.

[3] Dobson A., Krontiris A., Bekris K E., "Sparse Spanner Roadmaps", Workshop on the Algorithmic Foundations of Robotics (WAFR), June 2012.

[4] Grady D K., Bekris K E., Kavraki L E., "Asynchronous Distributed Motion Planning with Safety Guarantees under Second-Order Dynamics", Workshop on Algorithmic Foundations of Robotics (WAFR), Singapore, 13-15 Dec. 2010.

[5] Kimmel A., Dobson A., Bekris K E., "Maintaining Team Coherence under the Velocity Obstacle Framework", Eleventh International Conference on Autonomous Agents and Multiagent Systems (AAMAS), Valencia, Spain, June 2012.

[6] Krontiris A., Bekris K E., "Using Minimal Communication to Improve Decentralized Conflict Resolution for Non-holonomic Vehicles", IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS-11), San Francisco, CA, Sept., 2011.

[7] Li Y., Bekris K E., "Balancing State-Space Coverage in Planning with Dynamics", IEEE International Conference on Robotics and Automation (ICRA10), Anchorage, AK, May 2010.

[8] Li Y., Bekris K E., "Learning Approximate Cost-to-Go Metrics To Improve Sampling-based Motion Planning", International Conference on Robotics and Automation (ICRA-11), Shanghai, China, 9-13 May, 2011.

[9] Luna R., Bekris K E., "Network-Guided Multi-Robot Path Planning in Discrete Representations", IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'10), Taipei, Taiwan, pp. 4596 – 4602, Oct. 2010.

[10] Luna R., Bekris K E., "Efficient and Complete Centralized Multi-Robot Path Planning", IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS-11), San Francisco, CA, 25-30 Sept., 2011.

[11] Luna R., Bekris K E., "Push and Swap: Fast Cooperative Path-Finding with Completeness Guarantees", International Joint Conferences in Artificial Intelligence (IJCAI-11), Barcelona, Spain, pp. 294-300, 16-22 July, 2011.

[12] Luna R., Oyama A., Bekris K E., "Network-Guided Multi-Robot Path Planning for Resource-Constrained Planetary Rovers", 10th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS 2010), Sapporo, Japan, August 2010.

[13] Marble J., Bekris K E., "Asymptotically Near-Optimal is Good Enough for Motion Planning", Proc. of the 15th International Symposium on Robotics Research (ISRR-11), Flagstaff, AZ, 28. Aug. - 1 Sep, 2011.

[14] Marble J., Bekris K E., "Computing Spanners of Asymptotically Optimal Probabilistic Roadmaps", IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS-11), San Francisco, CA, 25-30 Sept., 2011.

[15] Marble J., Bekris K E., "Towards Small Asymptotically Near-Optimal Roadmaps", IEEE International Conference on Robotics and Automation (ICRA), Minnesota, MN, May, 2012.

[16] Sajid Q., Luna R., Bekris K E., "Multi-Agent Pathfinding with Simultaneous Execution of Single-Agent Primitives", Fifth Symposium on Combinatorial Search (SoCS), Niagara Falls, CA, July 19-21, 2012.

[17] Yuksel M., Bekris K E., Evrenosoglu C Y., Gunes M H., Fadali S., Etezadi-Amoli M., Harris F., "Open Cyber-Architecture for Electrical Energy Markets", 1st IEEE LCN Workshop on Smart Grid Networking Infrastructure, Denver, Colorado, USA, 11-14 October, 2010.

[18] Navkar, N. V., Deng, Z., Shah, D. J., Bekris, K. E., Tsekos, N., “Visual and Force-Feedback Guidance for Robot-Assisted Interventions in the Beating Heart with Real-Time MRI”, IEEE International Conference on Robotics and Automation (ICRA-12), Minneapolis, MN, 2012.

[19] Kimmel, A., Dobson, A., Littlefield, Z., Krontiris, A., Marble, J. and Bekris, K. E., “PRACSYS: An Extensible Architecture for Composing Controllers and Planners”, Simulation, Modeling and Programming for Autonomous Robots 2012, Tsukuba, Japan, Nov. 5-8, 2012.