Special Issue: Robotics Collaborative Technology Alliance (RCTA) Program

Editorial

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The growing technology investment in driverless cars, warehouse automation, human-service robots, and artificial intelligence applications in our daily lives is inspiring. However, the majority of this effort assumes a structured environment, which leaves significant, unsolved problems for autonomous robots operating in unstructured environments. Beginning in 2010, the U.S. Combat Capabilities Development Command, Army Research Laboratory (ARL), funded a 10-year research program, the Robotics Collaborative Technology Alliance (RCTA), which brought together scientists and engineers from government, academia, and industry to develop autonomous mobile robot technologies focused on solving the unique research challenges of operating in unstructured environments. While the underlying motivation came from helping soldiers operating in Army-relevant environments, the benefits extend to scenarios ranging from disasters, to planetary exploration, to reducing reliance on extensive prior knowledge in structured environments.

Initially, the program focused around four key robotics technology areas: perception, intelligence, human-robot interaction, and dexterous manipulation and unique mobility (DMUM). In the program's last several years, focus shifted to integrated capabilities, built upon the pillars of success already achieved. This revised, system-oriented approach laid the foundation for many experiments in laboratory, simulation, and field environments. The program concluded with a capstone demonstration that showcased advanced robotic capabilities for the stakeholders.

This special issue highlights robotics technology developed during the RCTA program, progress of which was evaluated and documented through research articles, field experiments, and hardware/software system descriptions. The program produced hundreds of published papers describing innovations in multiple, autonomy-related research areas throughout the program. The papers selected for this special issue describe more recent work, and range from individual research advances to lessons learned from conducting system-level field experiments. The following is a short summary of each paper.

- "Robotics CTA: 10 Years of Integration, Assessment, and Lessons Learned" by Quang et al. summarizes observations from the perspective of the entire 10-year RCTA program. Beyond advancing the state of the art by conducting research at some of the top academic institutions across the United States, the alliance also worked with top government and industrial partners to integrate the research into meaningful, militarily relevant experiments and demonstrations. This paper provides insight into the effectiveness of collaboration tools used by the

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geographically dispersed team, scaling the Robot Operating System (ROS) software framework across multiple platforms, conducting data collection efforts that result in usable datasets, and conducting frequent live and virtual experiments. The paper informs future efforts requiring disparate and distant teams of the potential advantages and disadvantages of such tools, along with lessons learned for how to most effectively work as a team of teams for advancing robotics.

- The paper "Using Perception Cues for Context-Aware Navigation in Dynamic Outdoor Environments" by Wigness et al. discusses an approach to the integration of several context-aware navigation behaviors on a small unmanned ground vehicle (UGV) and a perception stack that provides cues used to transition between these different learned behaviors. Specifically, this approach integrates socially compliant, terrain-aware, and covert behaviors in an outdoor navigation scenario where the UGV encounters moving pedestrians, different terrains, and weapon threats. The paper provides a detailed account of the overall system integration, experiment design, component- and system-level analysis, and lessons learned.
- The paper "Robust Object-Level Semantic Visual SLAM Using Semantic Keypoints" by Bowman et al. presents a semantic simultaneous localization and mapping (SLAM) algorithm that directly incorporates a sparse representation of objects into a factor-graph SLAM optimization, resulting in a system that is efficient, robust to varying object shapes and environments, and easy to incorporate into an existing SLAM pipeline. This keypoint-based representation facilitates robust detection in varying conditions and intraclass shape variation, as well as computational efficiency. Experimental results are shown from both RCTA field testing and with the KITTI data set.
- The paper "Semantic Keypoint-based Pose Estimation from Single RGB Frames" by Schmeckpeper et al. presents an approach to estimating the continuous six-degree-of-freedom (6-DoF) pose (3D translation and rotation) of an object from a single RGB image. The approach combines semantic keypoints predicted by a convolutional network (convnet) with a deformable shape model. The proposed approach can accurately recover the 6-DoF object pose for both instance- and class-based scenarios even against a cluttered background. The approach is applied both to several existing, large-scale datasets—including PASCAL3D+, LineMOD-Occluded, YCB-Video, and TUD-Light—and, using the authors' labeling pipeline, to a new dataset with novel object classes, which is introduced in this paper. Extensive empirical evaluations are described.
- The paper "Fast and High-Quality, GPU-based, Deliberative, Object-Pose Estimation" by Agarwal et al. proposes PERCH 2.0, a deliberative pose estimation approach that takes advantage of GPU acceleration and RGB data. This approach can achieve an order-of-magnitude speedup over PERCH (PErception via seaRCH) and meet scalability requirements for evaluating thousands of poses in parallel. The proposed work directly allows for an extension of deliberative pose estimation methods to new domains such as object articulation, conveyor picking, and 6-DoF pose estimation. The combined deliberative and discriminative framework for 6-DoF pose estimation achieves a higher accuracy than purely data-driven approaches, without the need for ground truth pose annotation.
- The paper "An Intelligence Architecture for Grounded Language Communication with Field Robots" by Howard et al. provides an architecture for grounded language communication that utilizes sensors and human guidance to interpret instructions conditioned on the environment. The architecture uses a model that describes both metric and semantic properties of objects, which are useful for grounding communication and planning, as well as the construction of behavior trees for complex task execution in unstructured environments. The resultant implementation was tested on multiple unmanned ground vehicles for language-guided navigation, manipulation, and bidirectional communication with human operators.
- The paper "Language Understanding for Field and Service Robots in A Priori Unknown Environments" by Walter et al. addresses the challenge of communication between robots and human teammates using natural language. This is an especially challenging topic when the robot and/or human does not have a perfect model of the world, but still needs to communicate

spatial information like navigation commands. Their approach develops a learning framework that treats language as an additional sensor into the robot in order to find a distribution of possible environments. The system is evaluated on real-world navigation and mobile manipulation problems on three robots.

- The paper "Human-Scale Mobile Manipulation Using RoMan" by Kessens et al. presents the design, integration, and complete software and hardware stack of RoMan, an articulated dual-arm manipulator system installed on a mobile, tracked base. The integrated technology includes all of navigation, perception, grasp planning, and motion planning; systems-level integration decisions and constraints are described. The resulting system was successfully tested on a heavy debris removal task and a container-opening/object-retrieval task in realistic field conditions.
- The paper "Grasping and Transport of Unstructured Collections of Massive Objects" by Bowkett et al. presents a system-level view of the problem of grasping and removing unknown objects from unstructured piles. The presented architecture autonomously deconstructs debris piles consisting of human-scale objects, visually selects suitable objects to move, plans object grasps, and extracts objects. The resulting system is tested on specific known objects and using a generic library of object prototypes and is able to successfully extract objects in a significant percentage of trials. Systems-level design lessons are also presented.
- The paper "Lessons Learned from two iterations of LLAMA, an Electrically Powered, Dynamic Quadruped Robot" by Jasper et al. describes the iterative design of a quadrupedal robot in the Legged Locomotion and Movement Adaption (LLAMA) project. This vehicle used custom quasi-direct-drive actuators powering three-degree-of-freedom, serial-parallel legs. The final design was capable of rapid motions of up to 1.8 m/s demonstrated over various terrains with a central energy management system that allowed for regenerated energy to be safely shared between limbs.
- In the paper "Quadrupedal Walking over Complex Terrain with a Quasi-Direct Drive Actuated Robot" by Griffin et al., the authors present a planning and control architecture for the LLAMA quadrupedal robot traversing rough terrain. The presented architecture identifies footholds, plans contacts using a graph-search or desired body path method, then plans a trajectory with a whole-body inverse dynamic control framework. The resultant system was capable of traversing rough terrain both indoors and outdoors and was tested both in the laboratory and in a field environment.

We hope that the papers presented here will provide insight and inspiration to other roboticists and that the work lays a foundation for continued research. The algorithms and software developed and tested have become part of the ARL autonomy stack, have been made available to other ongoing ARL program participants, and are being used in other government-funded robotics programs. We also feel it is important to note the invaluable transition of tacit and practical knowledge from engineers and scientists of this program to the existing and emerging robotics organizations in industry, academia, and government.

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