NRI WORKSHOP ON CLOUD ROBOTICS

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http://cloud-robotics.cs.umn.edu/index.html
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Summary

As cloud computing technologies mature, we can now think about creating robots that are not limited by either (1) speed or memory constraints or (2) availability of data. Cloud Robotics refers to approaches to robotics that exploit advances in cloud computing and big data, and have the potential for developing a new generation of robotics with many applications. This document summarizes the opportunities and challenges associated with Cloud Robotics.

The Opportunity

Applications such as the Google Car in which the Cloud is used for storing three dimensional maps give a sense of opportunities enabled by connecting robots to the Cloud. These opportunities can be summarized as follows:

1. Faster computation: Current algorithms for solving robotics problems such as path or manipulation planning are computationally intensive. The capability to ship these computations to the Cloud would be beneficial especially for resource-constrained robots such as micro aerial vehicles.
2. More data: By enabling access to “Big Data,” cloud-based approaches to robotics enable robots with access to “big data,” for example, a shared knowledge base for skills, objects and code.
3. Smarter and more adaptive: Cloud robotics allows sharing of data across machines, facilitating the development and evaluation of machine learning algorithms, which in turn will accelerate the rate of growth and development of robotics. Ultimately, the Cloud can enable a “shared brain” for robots.
4. Increased access: With cloud-based approaches, remote testbeds involving sophisticated (and expensive) robots and other devices can be made available to the broader community.
5. Networked machines: Cloud robotics can enable new paradigms for networks of machines in automation and manufacturing. The convergence of the global industrial system with the power of advanced computing, analytics, low-cost sensing and new levels of connectivity permitted by the Internet has also been called the *Industrial Internet* by General Electric.
6. Research and development: Cloud robotics also enables new paradigms for basic and applied robotics research, accelerating our progress toward new more capable robots. For example, just as large image databases have transformed object recognition in computer vision, large behavior databases can be used to train behavior recognition algorithms, so that robots can interact gracefully with humans.

Technical Challenges

The challenges which must be overcome before the full potential of Cloud Robotics can be realized are:

1. Most cloud robotics applications will require online connectivity to the cloud server. However, robotics applications can easily overwhelm bandwidth capacity of a network. Latency and reliability become crucial especially for real-time applications, and wireless links will create significant and highly variable bandwidth and delay bottlenecks.
2. Privacy and security issues associated with having cloud-connected robots operating in human spaces
3. Workload sharing: currently there is no clear understanding of what computations are better offloaded to the Cloud and which ones should be performed locally. Techniques for aggregating data (both on the robot and on the server) are needed.
4. Standards and protocols to share data, algorithms and code over the cloud are missing.

Cloud robotics would also inherit challenges associated with Cloud Computing in general such as the power requirements of cloud computing sites.

Recommendations for investment

1. Basic Research: In order to overcome the technical challenges listed above, basic research problems, such as the ones listed below, should be studied.
    - New architectures to distribute and manage local and cloud-based data and computation: Rather than returning a single solution (e.g. a motion plan), an approach in which the Cloud returns a set of solutions which can be further evaluated based on changing local conditions might help mitigate some of these issues associated with network availability.
    - Real-time Big Data: development of models for accessing the Cloud under various conditions, and bounds on system performance which can be achieved under these conditions. For example, access to an object recognition engine can be limited in a disaster response scenario. How would this affect the performance of a grasping algorithm?
    - Abstractions and Algorithms: What are interfaces for Cloud services that are general enough to be used by a large number of applications and simultaneously descriptive enough to facilitate the development of efficient algorithms?
    - Protocols for maintaining consistency on Cloud data and models in the presence of asynchronous updates

2. Challenges/Competitions: Examples of challenges that can catalyze Cloud Robotics Research are:
    - Household assistance in which robots perform household chores. Similar applications in elder care, child care and health care were also discussed. An application of interest is the use of robots for keeping living spaces clean, i.e., de-cluttering an office space or play room. Such a challenge will require robots to

perform high level reasoning about the state of the world in their attempts to recognize and manipulate objects while navigating in cluttered spaces. Successful systems will require seamless integration between the various perception, planning, and grasping components whose individual and collective performances can be significantly improved via access to Cloud resources.

- First responders, real-time threat detection and assessment in which robots collect data and simultaneously simulate all scenarios given information at hand using the Cloud
- Semantic Mapping and Labeling in which robots build a spatial map of objects augmented with information such as affordance. This system would be the basis of a larger system which can be used for robots to figure out where they are (similar to GPS), infer knowledge from sensory data and allow human-robot interaction using high-level language

3. Shared Infrastructure: An important aspect of a Cloud Robotics research program is a shared infrastructure which provides standardized software and hardware tools for executing code on standardized platforms. Such an infrastructure would lower the bar for entering the field and also provide a step toward building benchmarks, standardized development environments which are desperately needed for progress in robotics.

Workshop Participants

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