Cyber-Physical Systems:
Exploiting Morphological Diversity for Multi-Agent Intelligence

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***Abstract* – In the next 10-15 years, semi-autonomous robotic systems are poised to play an ever-increasing role to replace human counterparts as first responders and to provide assistance in the home. This position paper proposes a number of cyber-physical systems challenges, whose solution could accelerate the impact of these systems with methods that exploit morphological diversity in multi-agent teams of robots.**

I. Introduction

Whether on the front lines or in the home, robotic technologies are in a position to have great impact alongside or in place of human counterparts over the next 10-15 years. Domestic service robots have seen an annual growth of 20+%, and have made inroads in important application areas such as in the delivery of pharmaceuticals at hospitals [1]. Robots for defense and disaster recovery have received much attention lately, most notably with the DARPA Robotics Challenge [2]. In this grand challenge, teams are competing with a humanoid or other legged machine in a disaster recovery scenario inspired by the recent Fukushima disaster. Although mainly focused on humanoid robots, the future potential to supplement these robots with a morphologically diverse system of agents could allow new humanoids to operate more reliably and capably in challenging scenarios.

The inclusion of humanoid robots in the home and as first responders is motivated by their structural similarity to humans. This similarity makes them strong candidates to operate in spaces designed for human occupancy and provides the opportunity for natural human-to-robot interaction. Humanoid robots alone, however, have yet to make significant impact outside of the lab, due in part to the large centralized burden placed on the humanoid's sensing and planning as well as their difficulty to reliably maintain balance.

The use of a morphologically diverse set of agents, in conjunction with humanoid robots, provides a potential avenue to accelerate the impact of these robots. For instance, although the humanoid has advantages to perform manipulation tasks that require strength or dexterity, locomotion challenges make it difficult to gain perception information beyond their immediate area. The use of aerial vehicles or reliable wheeled vehicles would be more suitable to acquire this information to support of the humanoid's high-level efforts.

Although much research has focused on teams of robots with uniform structure, there are many new cyber-physical challenges in computational infrastructure that would need to be studied to enable ***diverse*** teams of legged and non-legged robots to intelligently plan and execute their ensemble behaviors. Important challenges in perception and strategic operator intervention are discussed here as a few key areas where new cyber-physical systems theory could benefit these applications.

II. Addressing 3D-Perception Through Cyber-Physical Coordination

3D perception is a main challenge facing current autonomous robots. Robust perception prevents current robots from operating reliably in unknown environments and is difficult for single-agent systems with limited maneuverability. For multi-agent teams, these systems will be able to strategically perceive a scene based on the geographic location of the agents as well as the reachability of nearby areas. In the process of developing real-time coordinated perception plans, these systems will need to balance the risk of travelling to assigned areas, and re-evaluate perception plans online based on each agent's ability to access assigned areas. System abstractions for each morphology will need to be developed and evaluated to ensure that agents are being used effectively.

Structural diversity among the agents will introduce diversity in the computing power present on each agent. This diversity will allow for distributed optimization algorithms to leverage computational resources differently on each robot for coordinated perception. New methods to make appropriate use of the relative computing power of individual agents will need to be developed.

3D perception is further complicated when working in dynamic environments where objects may be evolving continuously. The use of morphologically diverse agents would allow objects to be simultaneously studied from multiple viewpoints and presents additional challenges to be addressed in perception coordination algorithms.

III. Operator Intervention for Morphologically Diverse Systems

Semi-autonomous operation of humanoid robots will continue to be important over the next 10 years as these systems start to develop a higher degree of autonomy. By allowing for some level of human intervention, humanoid robots will make more immediate impact, while parallel advances continue in the areas of skill learning and AI. In multi-agent teams of diverse robots, operator intervention may be able to be avoided in favor of cooperation between agents. This cooperation will be different than in traditional multi-robot systems, as morphological diversity will give each agent marked advantages and disadvantages in how it might be able to interact with the physical world. This interaction richness will require operator intervention to script initial interactions.

Operator intervention in morphologically diverse systems will present difficulty to single operators. Natural interfaces will have to be developed to coordinate the rich interactions between agents. For instance, humanoid robots could be used to lift and transport smaller wheeled robots to previously inaccessible areas, such as over stairs in the home, or to a high ledge in disaster recovery scenario. In either situation, any operator intervention with the humanoid would require a high-level intention to be relayed to other agents such that they can react intelligently during the period of operator intervention.

The use of operator intervention would allow for coordination strategies to be learned. Methods for distributed coordination learning will be complicated by the morphological diversity of the agents, and will require new theory in multi-agent skill learning.

IV. Summary

The robotic systems of tomorrow will be integral components of daily life in domestic service and in dangerous first-response scenarios. Although current research has often focused on the use of a single morphology for use in any given application area, the synergy of abilities from a morphologically diverse team of robots has the opportunity to allow these systems to make a more immediate appearance in the home and front lines. Solutions to the cyber-physical challenges presented here could greatly boost the impacts that these coordinated teams could provide over single agent solutions.

[1] A Roadmap for U.S. Robotics From Internet to Robotics. http://robotics-vo.us/sites/default/files/2013%20Robotics%20Roadmap-rs.pdf.

[2] DRC Trails. http://www.theroboticschallenge.org.