A Shared Control Architecture for Human-in-the-Loop Robotics Applications

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Abstract

It is evident that over the last decade, the emergence of research in human-in-the-loop cyber physical systems (HiLCPS) in a very diverse set of application domains has encouraged innovative approaches to complex problems and challenges. Robots act as physical agents within a HiLCPS and they enable complex interaction with the environment. As a result there is a need to investigate, design, implement and validate novel shared control techniques to enable reliable, robust, and sufficiently agile interaction, communication, and operation in human-in-the-loop robot systems. We posit that there are certain tasks humans are (and will be) superior to robots such as perception, intuitive control, and high-level decision-making, on the other hand, there are tasks robots can (or should) perform such as precise low-level motion planning, solving an optimization problem, and operating in dirty, dull and dangerous situations. Therefore, the investigation of new control interfaces and shared control methods that can effectively delegate tasks and blend the control between the robot and human operator will enable us to field robot systems that act in direct support of humans.

It is possible to classify most robots that are currently deployed in applications in two categories: (i) fully autonomous robots performing specific tasks, and (ii) tele-operated robots with little to no intelligence. We acknowledge that not all human-robot interaction fall into these two categories but they represent a wide majority of systems that are currently in use. As we attempt to close the gap in between these two classes, new control techniques are needed to dynamically shift the level of control between the human operator and the intelligent robot using dynamical system modeling, stochastic control, probabilistic robotics, physical human-robot interaction, and systems engineering tools.

The development of HiLCPS has also led to the emergence in new challenges when trying to apply traditional tools to solve the associated problems. HiLCPS tend to involve collaborative development efforts with contributions from a wide variety of disciplines. Each discipline brings it own associated set of tools, metrics, and language which make collaboration more difficult than within a discipline. Understanding a key concept in one domain will not be sufficient for researcher in HiLCPS. The tools to encourage cross-domain collaboration are either non-existent or insufficient today.

In addition to a variety of disciplines, HiLCPS commonly span several different scales, from fine granular details at the lowest level to abstract coupling and interactions at the highest levels, at the same time. The flow of information and interfaces between the levels need to be well understood to grasp the operation of the HiLCPS, but without a formal methodology to analyze those interactions the complexities of the systems are lost or ignored as disturbances.

Challenges in HiLCPS

- Modeling of Human-in-the-Loop Cyber Physical Systems
  - Complex
  - Many loops for information
  - Non-traditional interfaces
  - Very asynchronous communication – hybrid systems
  - Model-based control and optimization
- Comparison of CPS implementations
  - Possible within the same application domain
  - Impossible across different domains
- Application domains
  - Vehicles and transportation systems
  - Underwater vehicles and robots
  - Space robotics and exploration
  - Disaster robotics
  - Assistive robotics

HiLCPS Science

Dynamics Equation

$$M(\eta)\,\ddot{\eta} + N(\eta,\dot{\eta}) = \tau$$

Constraint Equation

$$A(\eta)\dot{\eta} = 0$$

Can user intent be modeled as constraints on a traditional robot dynamical model?

The question that needs to be rigorously studied is that, under what circumstances we can model the human actions as constraints, and how can we quantify the uncertainties in human actions and cast them as uncertainties in terms of model parameters in this formalism.

HiLCPS Control Architecture

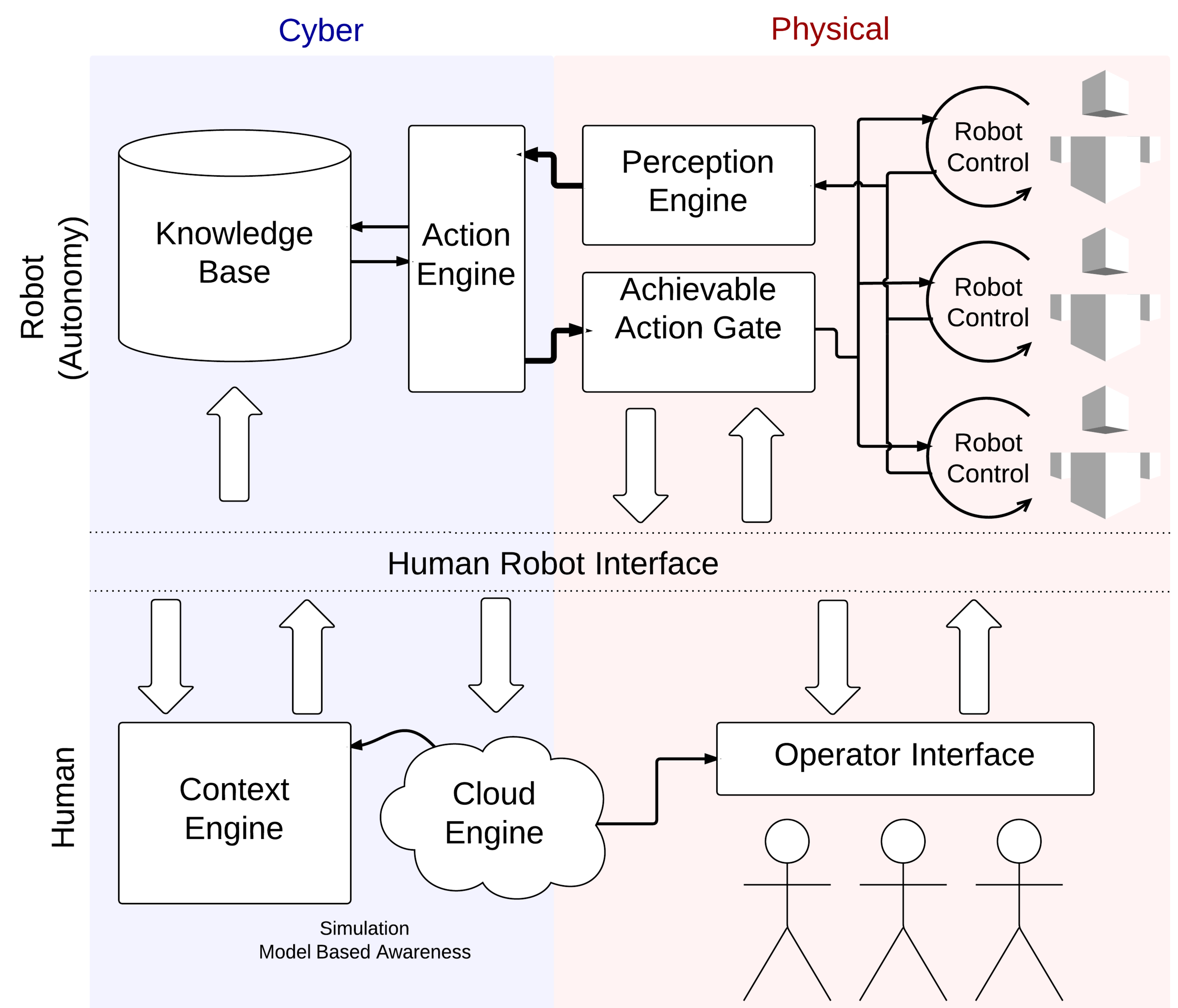


Figure 1: The proposed shared control architecture for modeling human-in-the-loop cyber physical systems. Each module is described in further detail below.

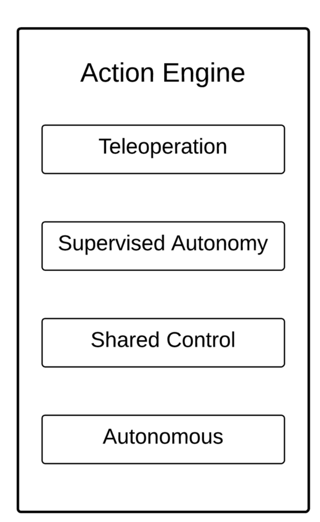


Figure 2: Several control modalities can be implemented in the action engine that can be changed dynamically.

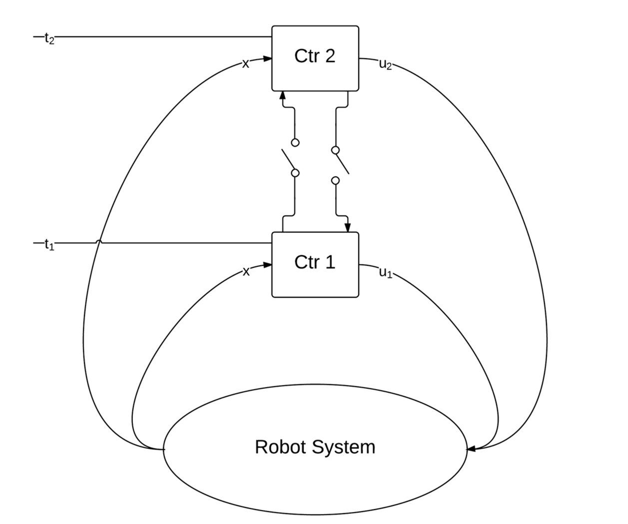


Figure 3: A proposed method for modeling the robot control modules. The controllers in many CPS have both series and parallel control structures.

Architecture Modules

The Knoweledge Base stores global strategies and approaches for the system, providing options to the action engine further down the line. For most systems, the knowledge base operates on an infrequent and asynchronous time frame, changing goals and approach on an event-based principle.

The Action Engine takes the global strategy and plan given by the knowledge base and generates a set of potential actions that the robots can take to achieve the tasks. The HiLCPS can be teleoperated, controlled through supervised or guarded autonomy, shared controlled, or fully autonomous.

The Perception Engine has a high-bandwidth, low-latency link with the robot sensors collecting and sorting the information from those sensors. The primary purpose of the perception engine is to interpret the sensor information and pass along only the information relevant to generating a set of desired actions to the action engine.

The Achievable Action Gate takes the desired actions provided by the action gate and checks if they are actually achievable and relevant for the system. The operator can change the desired actions through the action gate depending on the control modality.

The Robot Control block accepts the actions from the action gate and translates them to low-level commands that the motion controllers on each robot can accept and accomplish. We have identified that many HiLCPS have parallel and series control loops, and this is one of the intricacies that should be captured to enable comparison of cross domain HiLCPS.

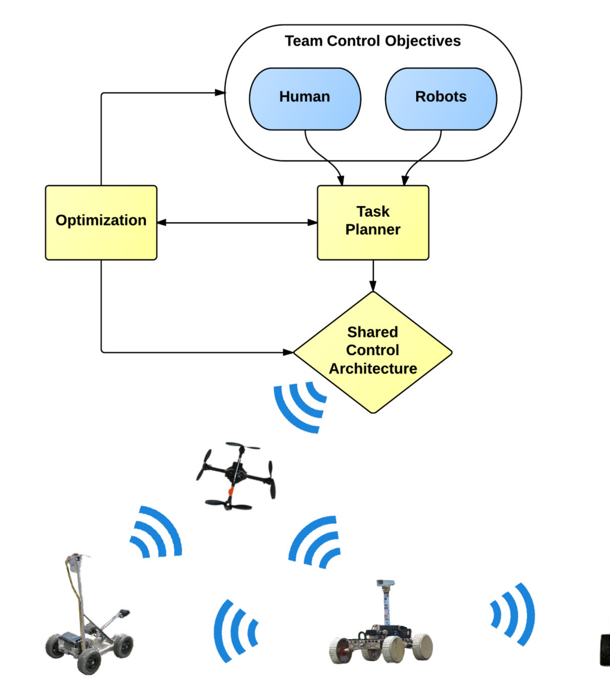
The Cloud Engine receives limited state information about the robot system through the human robot interface and passes the information to the cloud, harnessing the combination of significant human and computational resources, to provide simulations and model-based awareness and control improvements.

The Context Engine receives information from the human-robot interface similar to the cloud engine to understand the environment and situation around the robots. In addition, it can utilize the information from the cloud engine to help decipher the information and context in an accurate and efficient manner.

The Operator Interface serves as the carrier of information between the HiLCPS and the operator or potentially multiple operators. The interface can change based on the information provided by the cloud engine.

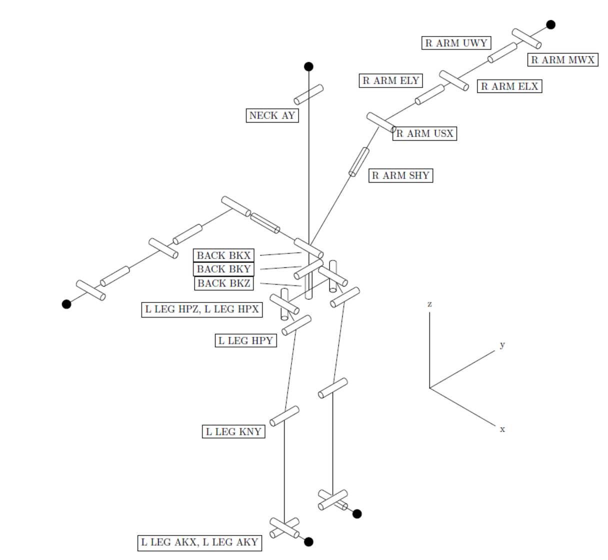
HiLCPS Applications

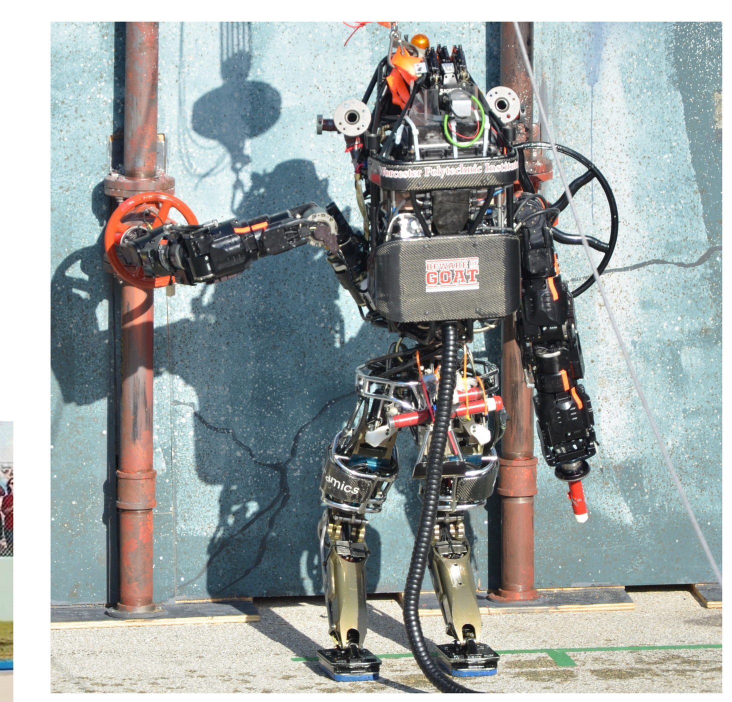
Space Robotics



Can human-robot exploration teams more effectively explore extraterrestrial environments?

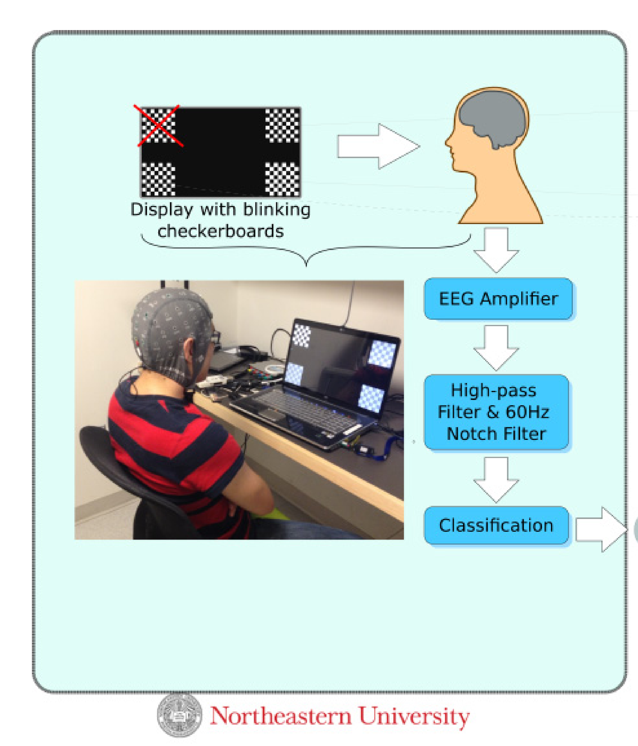
Disaster Robotics

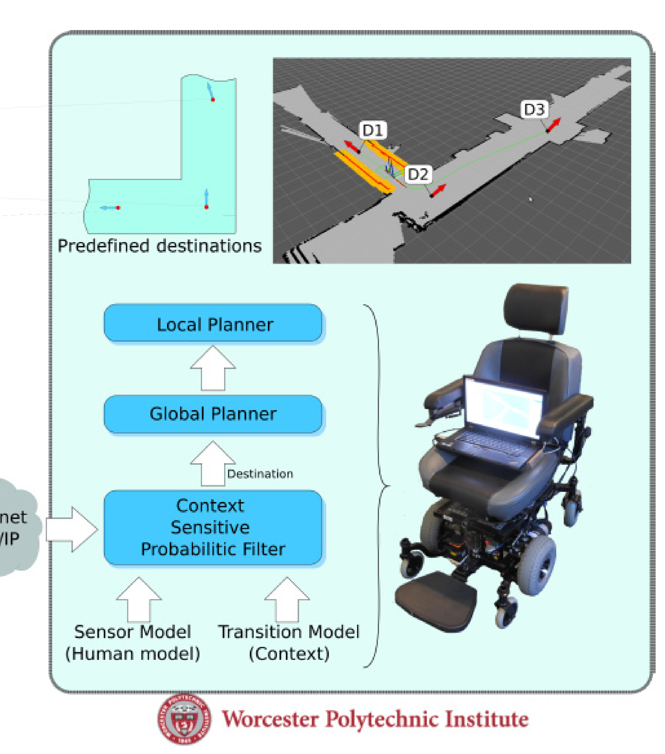




Can human-robot search and rescue teams conduct disaster response?

Assistive Robotics





Can semi-autonomous robots help individuals with disabilities improve their quality of life?

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