Dynamic-Autonomy for Remote Robotic Sensor Deployment

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Abstract

The INEEL is working to develop robots that can adjust their level of autonomy on the fly, leveraging their own, intrinsic intelligence to meet whatever level of control is handed down from the user. Sliding autonomy will support changing communication, cognitive, perceptual and action capabilities of the user and robot. Towards this objective the INEEL is working to provide robots that can actively protect themselves and the environment as they take initiative to accomplish task objectives. Such robots must continuously assess and respond to changes in the environment and their own perceptual capabilities and behavior. The INEEL has developed novel human-robot interaction (HRI) concepts and interfaces for robust, mixed-initiative interaction between robots and humans. These interfaces utilize simultaneous localization and mapping techniques that capture an abstracted representation of the robot's experience and exploit sensor-suites and fusion algorithms that enhance capabilities for sensing, interpreting, and "understanding" environmental features. This paper reports on the current robotic system including hardware, sensor suite, software control architecture, and interface systems.

I. INTRODUCTION

This paper describes research being conducted at the Idaho National Engineering and Environmental Laboratory (INEEL) in the area of robot control architectures and human robot interaction (HRI). The INEEL is researching and developing new and innovative tools for synergistic interaction between autonomous robots and human operators, peers and supervisors. This research is developing a control architecture that interleaves multiple levels of human intervention into the functioning of a robotic system that will, in turn, learn to scale its own level of initiative to meet whatever level of input is handed down. For a robotic system to gracefully accept a full spectrum of intervention possibilities, interaction issues cannot be handled merely as augmentations to a control system. Instead, opportunities for operator intervention must be incorporated as an integral part of the robot's intrinsic intelligence. The robot must be imbued with the ability to accept different levels and frequencies of intervention. Moreover, for autonomous capabilities to evolve, the robot must be able to recognize when help is needed from an operator and/or other robot and learn from these interactions.

This research is motivated by operational experience at the INEEL in conducting remote characterization of hazardous environment using robotic platforms. In addition, this effort will accelerate the state of the art in remote sensor deployment and pave the way for a new class of intelligent robots. Mobile robots used within DOE environments have been either teleoperated or fully autonomous. Teleoperated systems have often failed to address the limitations of telepresence inherent to current communication technologies. On the other hand, attempts to build and use autonomous systems have failed to acknowledge the inevitable boundaries to what the robot can perceive, understand, and decide apart from human input. Both approaches have failed to build upon the strengths of the robot and the human working as a cohesive unit. They have not leveraged off of the human's ability to teach and the robot's ability to learn.

The INEEL is working to develop control architectures and complete robotic systems that can adjust their level of autonomy on the fly, leveraging their own, intrinsic intelligence to meet whatever level of control is handed down from the user(s). The objective of this research is to design and develop an integrated robotics system, including hardware, software, and interface components through which optimal human *and* robotic perception, reasoning and action can occur.

Remote sensor deployment is already relevant to ongoing INEEL site operations and will become increasingly vital as more complex remote solutions are demanded. Human robot interaction (HRI) issues are not merely icing on the cake, but rather they are a driving force propelling robotics use in Environmental Management operations. Most importantly, the prevailing trend that forces humans to adapt to the limits of inflexible technology will give way to interface technologies that adapt to our needs, enabling a new era of human-machine interaction. Such technologies will not and should not ever be used to completely replace human workers or remove them entirely from the control loop. Rather, the architecture developed will present different kind of tools than any we have yet seen – “mixed initiative” machines that work with humans as well as for them.

II. BACKGROUND

As robotic technologies continue to advance, robotic solutions are increasing desired for conducting remote tasks and minimizing human exposure to hazardous environments. Remote characterization of high radiation environments is a pressing application area where robotic solutions can provide tremendous benefit. In 2001, the INEEL utilized a robotic system coupled with a Gamma Locating Device (GLD) to characterize an area which had been closed to human entry for many years. The DOE’s Environmental Restoration and Waste Management Robotics Technology Development Program explains that manual work within hazardous environments is slow and expensive. Worker efficiency is low due to protective clothing and exposure limits and small stay times require work to be accomplished in extremely short time intervals. Even when exposure limits are not an issue, fatigue is often induced by the personal protective equipment, confined working spaces and by the highly repetitive nature of certain tasks. The cost of a given project is increased because of the special materials needed to protect workers and the environment, and because of the additional wastes generated in the form of contaminated clothing, rags, tools, etc.. Moreover, time required to accomplish missions in hazardous environment is adversely impacted not only by low worker efficiency, but can also be impacted by the need to prepare the workers and instrument the site.

State of the art remote robotic operations have offered a means to remove the human from hazardous environments. The majority of these systems have used teleoperated robotic systems. These teleoperated systems, however, require high-fidelity video, reliable, continuous communication, and instrumentation of the environment with fiducials. In terms of operator workload, such systems require continuous, low-level input, without which they become useless, or worse, they become a liability. In fact, thick concrete shielding often makes it extremely difficult or impossible for high-bandwidth communication or video feedback to support strictly teleoperated systems. At best, teleoperated systems require months of preparation including training operators in mock-up environments. Not surprisingly the DOE roadmap for Robotics and Intelligent Machines states that in terms of time, cost and safety, ‘usability’ may well prove to be the most crucial component of robotic systems for remote characterization and handling of radioactive and hazardous materials. In short, this is a dangerous, costly task, which not only demands mixed-initiative control, but also provides us a unique opportunity to measure the benefits of mixed-initiative control within the near term through real field deployments.

III. ROBOT IMPLEMENTATION

In developing the mixed-initiative control architectures, we used a modified ATRVJr robot platform commercially available from iRobot. The ATRVJr was the same platform used by the INEEL in the GLD remote sensor deployment mentioned earlier. The GLD deployment provides a benchmark against which we can compare the mixed-initiative implementation. The ATRVJr was fitted with a Sony CCD camera that can pan, tilt and zoom to provide visual feedback to the user. The robot also uses this camera in the autonomous modes to characterize the environment and can automatically track people and objects, permitting the robot to autonomously follow a human or intercept an intruder, even at high speeds based on autonomous behaviors developed at the INEEL. The INEEL has successfully interfaced a forward looking infrared (FLIR) camera to an ATRVJr robot and has developed software that allows the data from this camera to be integrated into the robot control architecture. Fused data from the FLIR and CCD cameras will permit both autonomous and human-assisted recognition of relevant heat sources including fires and human heat signatures. These capabilities will be leveraged to meet perceptual challenges such as identifying an intruder and locating a fire.

Figure 1: Thermal camera mounted on robot

For this system to meet its goals, we must be able to guarantee that the robot will protect itself and the environment. To do so we fuse a variety of range sensor information. A laser range finder is mounted on the front, and 17 sonar located around the mid-section of the robot. The robot also has highly sensitive bump strips in the rear and front that register if anything has been touched. To protect the top of the robot, especially the cameras and mission-specific sensors placed on top of the robot, we have also added many infrared proximity sensors that indicate when an object is less than nine inches from the robot. Additional infrared proximity sensors have been placed on the bottom of the robot and point ahead of the robot towards the ground in order to prevent the robot from traveling into open space (e.g. traveling off of a landing down a stairway). Together these sensors provide a nearly impervious field of protection around the robot and allow the operator to command the robot with full confidence that the robot will not damage itself or its environment.

Figure 2: Instrumented robot platform

Obstacle avoidance is not sufficient for optimal human-robot interaction. Many adverse environments may include forms of uneven terrain such as rubble, which the robot must be able to recognize and respond. The robot has inertial sensors that provide acceleration data in three dimensions. This data is fused with information from the wheel encoders on the actual velocity and acceleration of the wheels and current draw from the batteries to produce a measure of the “unexpected” resistance encountered by the robot. The user can choose to set a resistance limit, which will automatically stop the robot once the specified threshold has been exceeded. The resistance limit is invaluable not only for rough terrain, but in situations when the user needs to override the “safe motion” capabilities (based on the obstacle avoidance sensors) to do things like push chairs and boxes out of the way or push doors open. In addition, the robot has tilt sensors that indicate pitch and roll.

To permit deployment within shielded structures, we have developed a customized communication protocol, which allows very low bandwidth communications to pass over a serial radio link only when needed. The interface itself then unfolds these simple packets into a comprehensive interface. The system will use at least three separate communications channels with the ability to reroute data when one or more connections is lost.

IV. CONTROL ARCHITECTURE

Our research to date has developed a control architecture that supports four distinct modes of remote intervention. For each of the levels of autonomy, perceptual data is fused into a specialized interface that provides the user with abstracted auditory, graphical and textual representations of the environment and task that are appropriate for the current mode. The intelligence necessary to support these modes of autonomy resides wholly on the robot itself -- no off-board processing is necessary. Future research will investigate if, when and on what basis we should allow the robot to recognize operator inefficiency or lack of input and autonomously adjust its own level of autonomy.

In discussing “mixed initiative” human robot interaction it is important to reflect upon the previous research conducted in automation and process control. Similar Human-Machine Interaction issues exists in both areas. Sheridan and Verplank introduced a scale to describe modes of human-machine interaction. [1, 2] These levels of interaction are:

1. Whole task done by human except for actual operation by machine
2. Human asks computer to suggest options and selects from the options
3. Computer suggests options to human
4. Computer suggests options and proposes one of them
5. Computer chooses an action and performs it if human approves
6. Computer chooses an action and performs it unless human disapproves
7. Computer chooses an action, performs it, and informs human
8. Computer does everything autonomously

Human Operator issues related to these various levels of autonomy include system productivity; operator trust in the autonomous system (i.e., operator's perception of the reliability of the system "advice"); operator self-confidence that he/she can step into the system and take over control from the machine; the operator skill level when direct control must be taken, and the operator's situation awareness.

These same issues are relevant in the use of mixed-initiative control for mobile robotic system. Additionally with a system that permits an operator to shift between levels of control, the potential for mode confusion exists. It is critical that interfaces be designed to mitigate the potentially adverse affects described above.

The robotics control architecture that the INEEL has developed supports the following four levels of control:

1. Teleoperation:
2. Safe Mode
3. Shared Control
4. Full Autonomy

A. Teleoperation

We have taken the interaction substrate used in previous INEEL teleoperated robotic systems and revamped it through feedback with people who have deployed such systems. Within teloperation mode, the user has full, continuous control of the robot at a low level. The robot takes no initiative except to stop once it recognizes that communications have failed. Because the robot takes no initiative in this mode, much work has gone into providing appropriate situation awareness to the user using perceptual data fused from many different sensors including laser, IR break beams, sonar, bump sensors, pan-tilt-zoom camera, thermal camera, inertial sensors, tilt sensors, magnetometer, compass, thermometer, and others. One of the innovative perceptual subsystems we have developed to provide situation awareness is a measure of resistance to robot movement. Inertial effects and abnormal torque measurements on the wheels are fused to produce a measure of resistance to robot movement as when the robot is climbing over or pushing against an obstacle. Even in teleoperated mode, the user can choose to activate a resistance limit that permits the robot to respond to high resistance and bump sensors.

B. Safe Mode

User directs movements of robot, but the robot takes initiative to protect itself. In doing so, this mode allows the user to issue motion commands with impunity, greatly accelerating the speed and confidence with which the user can accomplish remote tasks. The robot assesses its own status and surrounding environment to decide whether commands are safe. For example, the robot has excellent proprioception and will stop its motion just before a collision, placing minimal limits on the user to take the robot's immediate surroundings into account. The robot has many redundant and complementary sensors to insure that the robot will not harm itself or the environment including laser, sonar, IR, bump sensors. The robot notifies the user of environmental features (e.g., box canyon, corner, hallway) and immediate obstacles. The robot also continuously assesses the validity of its diverse sensor readings and communication capabilities. The robot will refuse to undertake a task if it does not have the ability (i.e. sufficient power or perceptual resources) to safely accomplish it.

C. Shared Control

The robot takes the initiative to choose its own path, responds autonomously to the environment, and works to accomplish local objectives. However, this initiative is primarily reactive rather than deliberative. In terms of navigation, the robot responds only to its local (~ 6-10 meter radius), sensed environment. Although the robot handles the low level navigation and obstacle avoidance, the user supplies intermittent input, often at the robot's request, to guide the robot in general directions. The problem of deciding how and when the robot should ask for help has been a major line of HRI enquiry and will be a major issue in our upcoming human subject experiments.

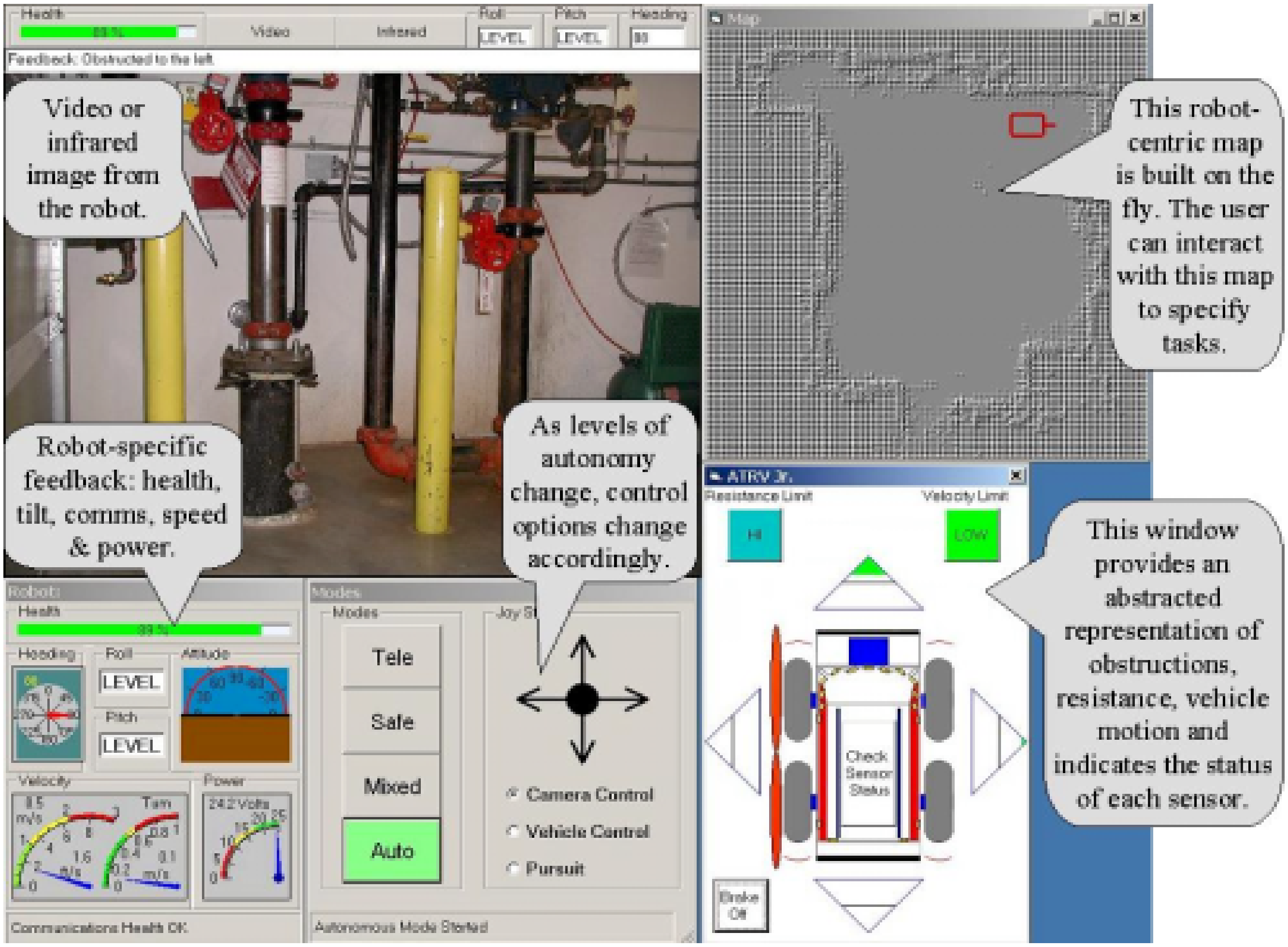
D. Full Autonomy

The robot performs global path planning to select its own routes, requiring no user input except high-level tasking such as "follow that target" or "search this area" (specified by drawing a circle around a given area on the map created by the robot). This map is built on the fly and uses frontier-based exploration and localization to perform searches over large areas including multiple rooms and corridors. The user interacts with the map to specify tasks and can guide the robot and infuse knowledge abstractly by selecting areas of interest and identifying sensed environmental features, which then become included within the map. One of the most challenging efforts thus far has been developing a “Get Unstuck” behavior that allows the robot to autonomously extricate itself from highly cluttered areas that are difficult for a remote operator to cope with.

V. HUMAN-ROBOT INTERACTION ISSUES

The inclusion of human-robotic systems into operational scenarios raises many issues in Human-Robot Interaction (HRI). These issues vary depending on whether the robot is operating in proximity of a human operator or if the robot is being monitored and controlled from a remote locations. In general these issues include situation awareness, vigilance in monitoring, mode confusion in control, and trust. Past interface and control systems for remote robotic systems have been complex in nature. In order to reduce the amount of training required for to operate such robotic systems, it is necessary to enable more natural interaction between humans and robots. This project will use multi-modal interfaces that include speech, natural language understanding, audible warnings and vibro-tactile alerts in addition to graphical and textual components. The most robust form of interaction is possible on the Remote Operator Console shown in figure 3. This remote operator console will be placed within a mobile van that can drive to any location. However, for many tasks, a large console is not necessary or possible. Operators who need a more portable interface can use a more compact interface which combines the various interface screens into one visual display.

Figure 3: Remote Operator Console



Feedback: Obstructed to the left.

Communications Health OK

Autonomous Mode Started

Figure 4: A screenshot of the current interface.

Currently, the graphical interface shown in Figure 4 is presented on a light-weight, portable touch screen. Special attention has been paid to how novel human-machine interfaces can explicitly reduce uncertainty for both human and robot. Humans should not have to guess at the intentions of a robot and, conversely, robots should not have to disambiguate or make inferences regarding uncertain human input. Interfaces that accomplish these goals will encourage operator trust and reduce human and robot error.

VI. CONCLUSION

The study of interaction between humans and intelligent, multi-operation robots presents a fascinating and crucial new area of research. A primary reason to undertake this effort is that great strides can be made in an area that cross-cuts almost all DOE mission needs. This study will take preliminary steps towards functional objectives set down in the RIM Critical Technology Roadmap including a personnel exposure reduction of 90%, a secondary waste reduction of 75%, and a productivity increase of 200% for Environmental Management (EM).[3] Although the proposed project will focus on a remote sensor deployment scenario, a wide spectrum of robotic technologies will benefit from this research including manufacturing robots, robots for decontamination and decommissioning purposes, mobile robots for environmental monitoring and long term stewardship, and mobile robots for urban search and rescue applications.

The DOE has placed emphasis on worker safety and the need for a cost-effective means to meet mandated clean-up milestones. If the functional objectives discussed above are any indication, enabling adjustable autonomy robots to be integrated into operations at the INEEL nuclear waste cleanup site will open a new chapter in approaching these goals. Like other self-accelerating technologies (e.g. the internet, computer processors), the application of RIM will start slowly but then accelerate under its own momentum. We must be sure to point this technology in a direction that is safe, healthy, convenient and productive for the humans who use it. In fact, one of the key emphases of this project will be to provide a context for fostering public and worker acceptance of robotics technologies.

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