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# An Autonomous Spherical Robot for Security Tasks

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***Abstract –*** *The use of remotely operated robotic systems in security related applications is becoming increasingly popular. However, the direct teleoperation interfaces commonly used today put a large amount of cognitive burden on the operators, thus seriously reducing the efficiency and reliability of these systems. We present an approach to alleviate this problem by exploiting both software and hardware autonomy. At the software level, we propose a variable autonomy control architecture that dynamically adapts the degree of autonomy of the robot in terms of control, perception, and interaction. At the hardware level, we rely on the intrinsic autonomy and robustness provided by the spherical morphology of our GroundBot robot. We also present a prototype system for facilitating the interaction between human operators and robots using our control architecture. This work is specifically aimed at increasing the effectiveness of the GroundBot robot for remote inspection tasks.*

***Keywords –*** *Mobile robots, Telerobotics, Telepresence, Site security monitoring, Virtual reality, Cooperative systems, Adjustable autonomy.*

## I. INTRODUCTION

The use of remotely operated robots is growing in many areas, ranging from underwater exploration to ground surveillance and disaster mitigation. The use of robots allows remote sensing and actuation without endangering human lives while increasing efficiency. In real remote inspection applications, operators are typically not robotics experts, but still have to use direct teleoperation interfaces that display "raw" data. This puts a great cognitive strain on the operators, who must concentrate on low-level tasks and leave insufficient resources to attend to high-level interpretation of information and decision-making tasks. It is therefore of interest to investigate techniques that make user interfaces intuitive and let operators maintain a high degree of situation awareness, thereby improving the robustness and reliability of teleoperated robotics.

The focus of the work reported in this paper is to facilitate human-robot collaboration in the performance of remote inspection tasks. These tasks can involve one or several operators assigned to investigate a remote area, using one or several mobile robots operating in the area. Potential applications include:

- Security surveillance of, possibly, large areas; for instance, to monitor the surroundings of airports or industrial plants to detect possible threats or intruders.
- Inspection of disaster areas to assess damages and potential hazards; for instance, to find and inspect gas tubes in buildings laid waste by fire, which might be at risk of explosion.
- Human search and rescue; for instance, to seek out, and assess the status of, survivors after earthquakes or avalanches.

The type of tasks above are characterized by the presence of two conflicting requirements when it comes to the modalities of interaction between the human operators and the remote robots.

On the one hand, one would like to delegate as much capabilities as possible to the remote robot, e.g., the capability to navigate around the area, to negotiate obstacles, to identify possible threats or survivors and use its sensors to acquire more information. In other words, we would like to endow the remote robot with a *high degree of autonomy*. This would lower the cognitive burden posed on the operator, who could rather concentrate on understanding the situation and making the right high-level decisions. This would also allow one single operator to control multiple robots at the same time and would increase the safety of the system, by ensuring that no important clue is missed due to distraction from fatigue on the operators part, and by allowing the robot to continue safe operation in the face of occasional loss of communication with the operator (e.g., radio loss).

On the other hand, there are good reasons why most current surveillance and inspection robots present a *low degree of autonomy*, in which the operator directly teleoperates the robot, often at the joint level. For instance, the system may require operator attention for careful maneuvers around an obstacle or on loose gravel, or for a decision of which area to explore first.

In our current work we tackle the above trade-off by exploring dual avenues to the remote operation of an inspection robot. We first present a *variable autonomy* control architecture, in which the robot can exhibit different types and degrees of autonomy, and dynamically switch between them depending on the context. Secondly, from a hardware point of view, we are exploring the *intrinsic autonomy* provided by a spherical morphology, which allows the robot to naturally, by its own morphology, negotiate obstacles and rough terrain. In the next section, we review some related work on degrees of autonomy in robot-operator interfaces. In the next two sections, we discuss our approach based on a combination of a variable autonomy architecture and a spherical morphology. Finally, we present a system under development, which facilitates collaboration between human operators and robots with variable autonomy.

## II. RELATED WORK

Fong and Thorpe [1] have distinguished four categories of vehicle teleoperation interfaces. The remote inspection robot interfaces mentioned above fall into the first category, the *direct interface*; this is the traditional and still common method for vehicle teleoperation. The operator typically controls the vehicle via hand-controllers while watching video from vehicle mounted cameras. This type of interface is appropriate when real-time human decision making or control is required. The *multi-sensor/multi-modal interface* combines information from several sensors or data sources to present a single integrated view, and gives the operator the opportunity to select different control and display modes. This type of interface provides efficient command generation and information-rich feedback. It can be used where the operator might have difficulty to perceive the environment or make timely control decisions. The *supervisory control interface* is designed for high-level command generation, monitoring and diagnosis. It allows the operator to divide the main problem into a sequence of subtasks which the robot can, due to some level of autonomy, execute on its own. Finally, the *novel interfaces* use unconventional input methods or displays, e.g., brain wave or muscle movement monitoring, or web-based interfaces. Interfaces are also characterized as novel if they are used in an unusual way, e.g., a system where the teleoperated vehicle serves as a fully mobile, physical proxy for the operator.

The current teleoperation paradigms leave operators wanting for interfaces designed for intuitive use that deliver an adequate amount of situation awareness. For instance, experiments set in a search and rescue scenario have shown that a majority of the operator time was spent trying to perceive and comprehend the situation, and only a minority of the time was spent on planning, projecting, and problem-solving activities [2]. In response to these kinds of issues, Baker et al. [3] have formulated the following set of general design guidelines for improved human-robot interaction.

- *Enhance awareness*; this can be achieved by providing more spatial information about the robot in the environment.
- *Lower cognitive load*; e.g. by fusing sensor information, which allows an operator to focus on a single area of the interface.
- *Increase efficiency*; if possible, support interaction with multiple robots in a single window; in general, minimize the use of multiple windows.
- *Provide help in choosing robot modality.* The interface should assist the user to determine the most appropriate level of autonomy.

The level of autonomy can be changed during operation, not only by a human user but by another system, or the autonomous system itself. This is referred to as *variable or adjustable autonomy* (AA) and, for instance, Goodrich et al. [4] distinguish between four different autonomy modes: intelligent teleoperation, way-points and heuristics, goal-biased autonomy, and full autonomy. While most systems with AA ability use discrete levels of autonomy, there is some work on continuous variable autonomy available [5]. The general problem of AA, formally defined by Scerri et al. [6], is to choose the level of autonomy that maximizes the overall utility of the team (where the team might consist of a constellation of multiple robots and operators, or just a single robot with an operator).

The guidelines of Baker et al. push development of human-robot interfaces toward multi-modal/multi-sensor designs. For example, there are already several examples [7], [8], [9], [10] of interfaces that use virtual reality (VR) or augmented reality (AR) displays to achieve the goals of the guidelines. These interfaces have a natural way to convey spatial information in a single view, and they possess a versatility that places them in all of Fong and Thorpe's classes. A robot-centric view-point provides a classic direct teleoperation interface, while a bird's eye view can provide a suitable interface for high-level tasks, such as mission planning. With a free view-point, VR interfaces also provide natural ways to interact at different levels of robot autonomy.

The use of interfaces based on augmented reality environments for *ball-shaped robots* have also been reported by Suomela and Ylikorpi [11]. They also recognize a number of advantageous properties of spherical robots, such as stability and robustness, that make them especially suitable for surveillance and, to some extent, search and rescue tasks [12], [13]. However, they also acknowledge some technical difficulties with spherical robots. For example, ball-shaped robots present a number of challenges in terms of control and perception. Any change in motion induces unwanted oscillations that are hard to rectify; Suomela and Ylikorpi [11] mention the robot Rollo that controls oscillation only around the rolling axis. They also mention Rotundus AB [14], which have previously put some effort into controlling the sideways oscillation of their spherical robot GroundBot. Spherical robots offer limited freedom in placement of sensors; for example, the most natural place for video cameras are at the point where the main axle meets the shell. Together with any oscillation, this placement easily disorientates operators, as established by Johansson and Seeman [15].

## III. VARIABLE AUTONOMY CONTROL ARCHITECTURE

To enable tasks requiring both a high degree of autonomy as well as tasks under careful teleoperated control of an operator

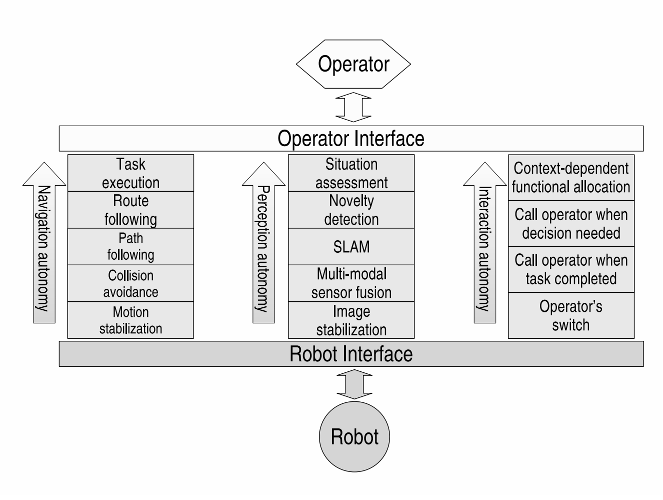


Fig. 1. Illustration of the three towers of autonomy.

we introduce the notion of a *triple tower of autonomy* dealing with variable degrees of autonomy in three different respects: control, perception, and interaction. See figure 1 for an illustration of this concept.

*Control autonomy* is the type of autonomy most often considered in robotics. This typically entails routines for (semi-)-automatic navigation giving goals that range from velocity set-points, position way-points, or specifications of full navigation tasks. Examples of increasing degrees of navigational autonomy include:

1. Stabilizing movements, for instance, automatic correction for wheel slippage.
2. Path following, way-point navigation and collision avoidance.
3. Full route following and path planning.
4. Fully autonomous search and monitoring in a given area.

*Perceptual autonomy* deals with the processing and presentation of sensor data. In its simplest form, sensor data are presented in raw form, e.g., images from a remote camera. By incorporating more advanced processing, the interface to the operator can be improved. Examples of increasing degrees of perceptual autonomy include:

1. Unprocessed sensor data presented in human readable format, for instance, raw camera images.
2. Fusion of sensor data over time or across sensors, for example, registering and visualizing a set of camera images taken over a time interval.
3. Fusion of data from heterogeneous sources, such as, overlaying the images from a camera with GIS information.
4. Advanced interpretaton of sensor data, for example, simultaneous localization and mapping (SLAM), object classifications, or novelty detection.

*Interaction autonomy* is the final type of autonomy that we are considering and is one which so far has received relatively little attention in the literature. This autonomy entails the ability to dynamically adapt the other two degrees of autonomy. In its simplest form, this is done manually by the operator. Although not yet implemented, we plan to study higher degrees of autonomy, including alerting operators in abnormal situations up to full situation assessment and automatic distribution of tasks to the robot and the operator. An important aspect in this autonomy is that the system should be able to assess what constitutes an abnormal situation. For instance, a robot navigating in an autonomous mode may detect a possible victim, and hence call the attention of the human operator. In the reverse direction, a robot being operated may detect a loss of contact (e.g., because of entering radio shadow or because the operator's attention being diverted) and hence jump to a higher degree of autonomy until contact with the operator can be re-established.

## IV. HARDWARE & MORPHOLOGY INTRINSIC AUTONOMY

This project currently uses the spherical security robot GroundBot from Rotundus AB [14] which is a ball-shaped robot with a diameter of 60 cm. This robot is capable of navigating rough outdoor terrain at speeds approaching 3 m/s (just under 7 mph). As a spherical robot, both locomotion and steering of the GroundBot is accomplished by displacement of its center of mass. Almost all of the robot's weight is suspended on a rigid axle mounted through the shell. The distribution of this weight is managed by two perpendicular motors able to rotate the weight about the robot's center. The robot is equipped with a PC/104+ format computer with an 800 MHz Crusoe CPU, a long-range 802.11a/g wireless network card, two motor controllers, loudspeaker, and a Lithium ion battery pack able to provide power for up to 12 hours of runtime. The current sensor outfit includes two pan/tilt zoom network video cameras, a Global Positioning System unit that makes use of differential GPS signals, microphones, and a Microstrain 3DM-GX1 gyro enhanced orientation sensor. See figure 2 for an image of this platform.

The cameras have an optical zoom ratio of $18 : 1$ ($216 : 1$ with digital zoom), and work both in daylight and low lighting conditions with an illumination of less than $0.01$ lx. They can deliver MPEG-4 compressed video streams with bit rates up to 2 Mb/s, or JPEG still image streams. Selectable video image resolution ranges from $160 \times 120$ to $640 \times 480$. They also provide bi-directional audio channels, and built-in motion detection. [16]

The intrinsic autonomy provided by a spherical morphology allows the robot to naturally negotiate rough terrain and sufficiently small obstacles, simply by rolling over them. Ball-shaped robots have a number of favourable advantages, such as stability and robustness, making them especially suitable for the types of applications we are considering. However, their shape and tendency to oscillate present problems with, for example, camera image stabilization, as mentioned in section II.

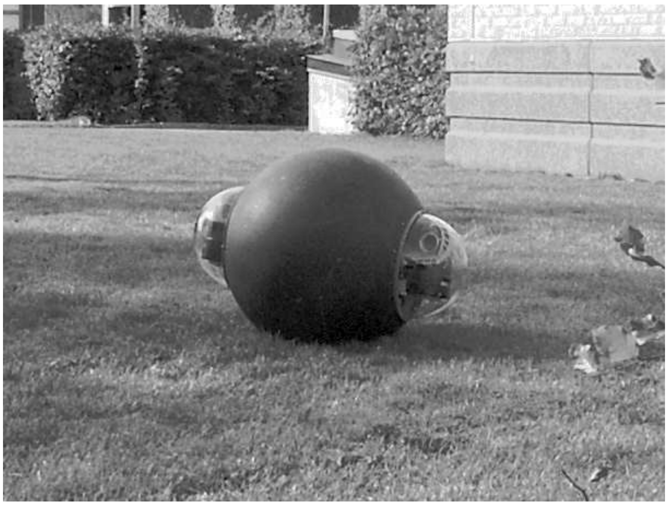

Fig. 2. The spherical security robot GroundBot.

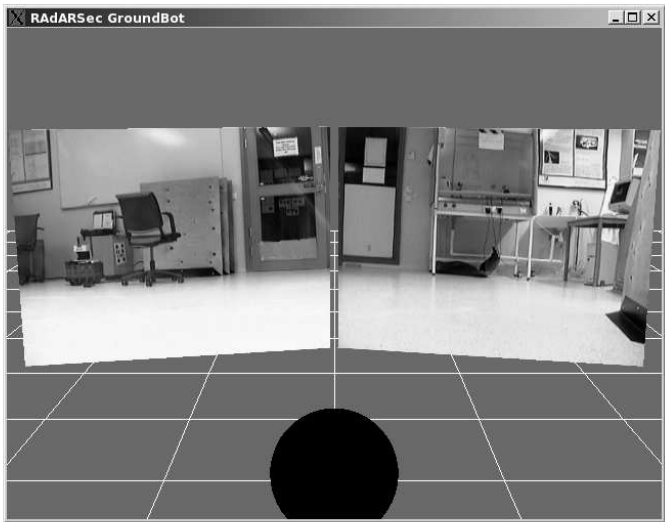


Fig. 4. Screenshot of our graphical user interface in use. The camera position is brought down to a third person view, overlooking the black ball-shaped GroundBot.

## V. A PROTOTYPE SYSTEM FOR HUMAN-ROBOT COLLABORATION

Here we present a system under development, which facilitates collaboration between human operators and robots using our variable autonomy control architecture, specifically in the performance of remote inspection tasks. The *shared perceptual space* we propose is a general tool for collaboration amongst humans and robots. The graphical user interface with *augmented virtual reality visualization* we present is an attempt to alleviate the problems with control and perception, directly related to a spherical robot.

### *A. Shared Perceptual Space*

In our research work, we do not assume a one-to-one correspondence between operators and robot, but consider cases possibly involving multiple robots and/or one or more operators.

When dealing with more advanced usage cases, such as multiple robots and/or multiple operators, robot-operator interactions become more complex. Our approach to dealing with these situations is a shared perceptual space, a blackboard model commonly used in robotics and AI, in which sensor readings and processed results can be shared between individual robots and the different interfaces to them, see figure 3. Using this method, operators can benefit from the sensor readings and local goals of other participating robot/operator units.

Panda3D is an open-source 3D engine library, now developed jointly by Disney and Carnegie Mellon University's Entertainment Technology Center [17]. Using Panda3D to implement this shared perceptual space dramatically simplifies the process of sharing information between participants, regardless of whether they are robotic or human. Panda3D has a transparent server architecture and distributed object model [18], originally developed for a commercial massively multiplayer online game, that allows for simple sharing of detailed environments.

### *B. Visualization*

Panda3D is also used for our new three-dimensional mixed-reality graphical user interface. Using a 3D interface gives us new ways to address challenges, introduced by the GroundBot's spherical shape, such as representing sensor readings and exercising control. For example, it is easy to imagine serveral useful ways to present stabilized images from a robot's cameras in the 3D environment. The pan-tilt ability of the GroundBot's cameras can give us a virtual $360°$ panoramic image of the robot's surroundings, or possibly track an object of interest in the world. To minimize the lag effect of network and execution time, an operator's display is quickened locally. To some extent, this gives the operator instant feedback on performed actions and the new state of the world. It is then the task of a robot to mimic quickened actions, in order to bring the real world into accordance with its desired state.

Another direct advantage of using a 3D interface with a controllable point of view is the ability to seemlessly move between different control paradigms. On one end, we have a classic, first-person teleoperation view of the environment, well suited for manually exploring an uncharted area. On the other end, we have a supervisory, birds-eye view of the world, desirable for tasks involving surveillance of known areas and controlling several robots exhibiting some higher form of autonomy. A view from this interface are presented in figure 4.

## VI. CONCLUSIONS

In the work presented here, we are currently developing a system for remote control of spherical robots using a varying degree of autonomy. One of the main reasons to develop autonomy features is the need to free guards from monotonous

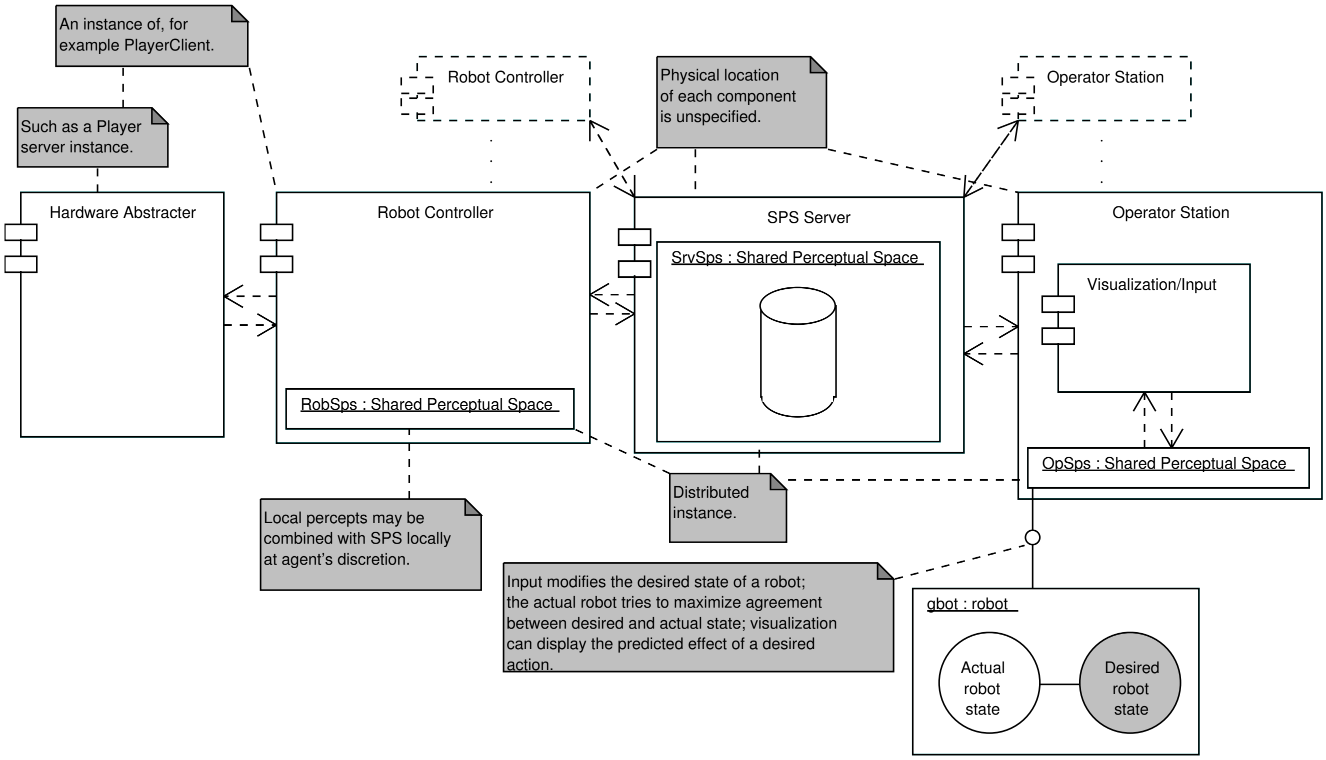


Fig. 3. Software architecture overview.

patrolling, increasing security and lowering costs. By using two or more robots working in overlapping shifts, perimeter protection can be maintained 24 hours a day, 7 days a week. In addition to security, the GroundBot is also expected to have applications within other areas such as search and rescue, disaster mitigation and general surveillance.

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