Abstract
For tasks that need to be accomplished in unconstrained environments, as in the case of Urban Search and Rescue (USAR), human-robot collaboration is considered as an indispensable component. Collaboration is based on accurate models of robot and human perception consistent with one another, so that exchange of information critical to the accomplishment of a task is performed efficiently and in a simplified fashion to minimize the interaction overhead. In this paper, we highlight the features of a human-robot team, i.e. how robot perception may be combined with human perception based on a task-driven direction for USAR. We elaborate on the design of the components of a mixed-initiative system wherein a task assigned to the robot is planned and executed jointly with the human operator as a result of their interaction. Our description is solidified by demonstrating the application of mixed-initiative planning in a number of examples related to the morphological adaptation of the rescue robot.

Introduction
Urban Search and Rescue (USAR) has largely drawn the interest of robotics research in view of the various hazards that could threaten the integrity of human rescuers in contrast to the agility as well as dispensability of robots that renders them invaluable assistants. Developing a system that exploits the complementary nature of human and automated reasoning can boost the efficiency in the execution of a task. Mixed-initiative robotic systems integrate human and automated reasoning to take advantage of their complementary reasoning styles and computational strengths (Ai-Chang et al. 2004; Bruemmer et al. 2005; Nielsen, Few, and Athey 2008). In order to achieve this, human-robot interaction (HRI) is deployed by modelling the robot and human perception in a reciprocal design that maximizes the information provided to the human and the feedback given to the robot that is useful for jointly accomplishing a given task (Chen, Haas, and Barnes 2007; Goodrich and Schultz 2007; Labonte, Boissy, and Michaud 2010).

Fundamental issues in mixed-initiative reasoning include distributing the responsibilities between the human and the robot for the tasks that need to be performed, the switching of control between the human and the robot, the exchange of information between the human and the agent, including mixed-initiative dialogue and multi-modal interfaces and the maintenance of a shared awareness with respect to the current state of the human and the agent.

Shared situation awareness is performed via a human-robot interface (Drury, Scholtz, and Yanco 2003; Scholtz et al. 2004) built upon the models of perception for the human and the robot, hence bridging the two domains. Sharing knowledge is in the benefit of accomplishing a task compared to distinct states of awareness, wherein the human and the robot operate as individuals. The basis upon which a shared situation awareness model is built is low-level perception of the environment through the robotic sensors (e.g. metrical mapping) and high-level perception through suitable combination of the sensory data into meaningful representations.

In this work we describe a mixed-initiative planning approach that is particularly useful for a contemporary rescue robot able to adapt its morphological configuration in order to operate in a diverse environment, such as in USAR. We deploy a model-based executive monitoring system (Williams et al. 2003; Carbone et al. 2008) to coordinate the operator’s interventions and the concurrent activities of the rescue rover. We explain how this approach enhances both the operator’s situation awareness and human-robot interaction for the execution and control of diverse activities within USAR (Carbone et al. 2005; Finzi 2005) by illustration of characteristic examples. In the following sections, we first describe the core components of the rescue robot (platform, perception, interface, HRI, model-based control), then describe the process of learning to flexibly adapt the morphology of the robot and finally unfold our approach on mixed-initiative planning in a number of examples.

The rescue robot control
Sensors and robot design
The robotic platform is similar to a space rover (see Figure 1); two bogies on the sides are linked to a central body containing the electronics. Each bogie is made of a central
Multi-modal robot Perception
The mobile robot system integrates into the Robot Operating System (ROS) (Quigley et al. 2009) multi-modal perception from vision and mapping with action planning.

Visual perception of the environment is performed by object (e.g. signs, cars) detection and localization using an omnidirectional camera. Object detection is performed using several learnable detectors that are rapidly updated while 3D localization is estimated via several object detections that are used by a greedy algorithm based on RANSAC (Hurych, Zimmermann, and Svoboda 2011). Furthermore, features of the terrain could be captured and used in order to perform terrain classification through vision (Wurm et al. 2009) or combined with depth data acquired from a laser (Manduchi et al. 2005). A metrical map of the environment can be obtained by visual odometry (Scaramuzza 2008), (Nister, Naroditsky, and Bergen 2004) or a SLAM algorithm using laser sensory data.

In order to illustrate our approach on planning the configuration of the morphology of the rescue robot, we assume that the robot is able to localize itself within a given 3D map of the environment, derive its orientation/acceleration using the IMU as well as recognize the characteristics of the terrain.

We can then translate the data structures coming from the different perceptual modalities into a suitable logical representation which allows the planning engine to reason about actions (Gianni et al. 2011) and generate appropriate plans.

Human-Robot Interface
The human and the robot interact through an Operator Control Unit (OCU) designed according to a model of situated dialogue processing (Kruijff, Janíček, and Lison 2010). The OCU plays a crucial role to model the interaction in terms of interplay between supervised autonomy (the operator is part of the control loop) and full autonomy (the operator has to lean upon the robot planned activities). The OCU provides the operator with a visualized map, camera stream, as well as plan and dialogue histories. The OCU facilitates multi-modal interaction: The operator and the robot can use spoken dialogue to interact, and the operator can use pointing gestures (mouse) to select waypoints or landmarks for the robot to go to. In this setting, the operator takes advantage of the robot perceptual capabilities which purposely draw his attention towards the current status of task, while he interacts with the mixed initiative reactive planner (Ai-Chang et al. 2004; Drury, Scholtz, and Yanco 2003).

The model-based control
The robot control is endowed with a declarative temporal model of the controllable activities. The declarative temporal model is specified in the Temporal Flexible Situation Calculus (TFSC) (Finzi and Pirri 2005) and explicitly represents the main components and processes of the robot system (e.g. slam, navigation, vision, differential, flippers), the cause-effect relationships as well as the temporal constraints among the processes (Gianni et al. 2011).

Furthermore, formal methods and reasoning engines are deployed to check for consistency, monitor the executions, perform planning and diagnosis. In a mixed-initiative setting the aim of the model-based system is to explicitly model the operator activities and to provide a view of the system that is intuitive and comprehended by humans so that the operator can supervise the robot status in a suitable human robot interface.

Learning the executive control
According to the previous description of the sensors of the robot, there is no perceptual feedback from the flippers and bogies with respect to the contact of the tracks with the ground.

Combining the feedback from the remaining sensors installed on the robot the model-based executive control should be able to generate a suitable set of parametric actions in order to flexibly adapt the morphological configuration of the robot. We begin by learning the control strategy through a simulated environment using an appropriate model of the kinematics of the robot that naturally interacts within the environment using a physics engine (Gazebo simulator in ROS (Quigley et al. 2009)).
Adapting the kinematic configuration of the rescue robot

The rescue robot is designed to operate on uneven terrain. As such, it should be able to configure its morphology in order to reduce instabilities that could cause the tip-over (McGhee and Frank 1968), (Papadopoulos and Rey 1996) of the robot. In order to optimally adapt the pose and morphology of the robot with respect to the terrain, we need to formulate an optimization problem for maximizing the surface contact of the tracks of the bogies and the flippers with the ground, relying on the estimation of the contact angles between the terrain and the tracks as estimated from the onboard sensors. For the particular rescue robot under consideration, maximizing the surface contact is a meaningful criterion in order to maximize the traction efficiency of the robot which in parallel results in minimized pressure on the tracks.

A measure of optimal robot pose can be defined combining together additional criteria (Freitas et al. 2010) (e.g. ground clearance, robot gradient stability margin), that would be used to derive an optimization problem. Using a sufficiently large variety of terrain maps (some examples are shown in Figure 2) that are characterized from the different ranges of the parameters involved in the optimization, we solve the optimization problem off-line within the simulation environment and hence compute the distributions of the involved parameters. This off-line stage constitutes the learning phase where the necessary skills for the morphological adaptation are learned and later employed in the real scenario wherein the robot would be asked to traverse uneven terrain.

Solving the optimization problem is time and resource consuming, hence it is performed off-line for the purpose of learning. However, in the case where the learned values of the parameters (velocity, flippers rotation, acceleration, etc) result in a failure to compute a suitable morphological configuration of the robot, the problem could be solved on-line as well, possibly with alternative initializations or weights for the various optimality criteria.

The control loop

Given the declarative temporal model of the controllable activities of the robot, a reactive planning engine monitors the low-level status of the system and the operator’s interventions, by continuously performing sense-plan-act cycles (Finzi, Ingrand, and Muscettola 2004).

In the sensing phase the model-based executive control of the rescue rover receives from each single component its current status as well as the terrain characteristics as derived from the 3D point cloud and color images. Combining the geometrical and visual interpretation of the area around the vehicle we could recognize the different classes of the terrain as well as isolated obstacles.

Once the execution context is provided in terms of the internal status of the robot, obstacles and terrain type, the reactive planning engine computes a route toward a desired waypoint, selecting a suitable kinematic configuration of the robot to cope with specific scenarios (as in Figure 2). The set of the parameters of actions (e.g. flippers angle, velocity, acceleration) are selected according to the learning process described in the previous section. During the execution phase, actions are performed and monitored with respect to their consistency and failures are managed by checking at regular time intervals the status of the system with respect to the performed actions.

Mixed Initiative Planning

Due to errors occurring in perception or estimation of the parameters of the configuration, a traversal task could fail and in these cases mixed-initiative planning proves particularly useful. Based on the interactive robot control described in the previous section we can define a number of mixed-initiative operational modalities lying between autonomous and teleoperated modes that are crucial in a collaborative planning setting. These modalities depend on the way in which the operator interacts with the system. Once the temporal plan is generated, the human operator can extend or reduce the duration of the scheduled activities in order to make it more efficient in terms of allocated time. In this modality, the model-based monitoring system has to check the consistency of the temporal constraint network of activities. The human operator can modify the control sequence produced by the planner by skipping some activities, adding new actions or take the control of some functional activities while the robot is executing a task. In this setting the model-based monitoring system builds the novel plan, under the human direction and validates the operator’s choices while in the case of safety constraints violations, it initiates appropriate
recovery operations and suggests suitable corrections to the operator. These modalities enable maximal flexibility for the initiatives of the planner and the human. They can exchange information and work in a concurrent way contributing to completion of the mission.

In the following, we show the benefit of the mixed-initiative approach in augmenting the situation awareness of the rescue robot and completing its mission.

**Improving the mobility of the robot**

The interventions of the human operator are regarded as exogenous events that modify the internal state of the robot while the model-based executive control has to check the discrepancies between the state of the robot components and the internal representation, recovering from such discrepancies. In this kind of interaction the operator initiative interferes with the planning activity with respect to the misalignments between the control plan and the state of the system.

A characteristic example concerns the case wherein the robot is halted due to the failure of the navigation component to compute a path toward a desired waypoint caused by the current morphological configuration of the robot (see Figure 3). By changing the position of the flippers, the size of the footprint of the robot could be reduced and hence improve its mobility. When the human operator recognizes this situation he can take the direct control of the robot and raise the flippers in order to allow the navigation component to compute a path.

**Improving perception by resolving partial occlusions**

In this example, we consider that the task of the robot is to explore an unknown area, map and report detected objects to the operator. The operator may not have a complete perception of the environment through the OCU or the vision component of the robot may not detect an object in the environment because the flippers of the robot obscure one or more sides of the omnicamera partially occluding the object of interest (see Figure 4). In this scenario the operator could modify the position of the flipper which is in the field of view of the sensor, without suspending the scheduled activities of the robot. The rescue robot control will react to this asynchronous event produced by the human intervention, updating only the current status of the robot pose. The human operator would have an improved perception of the area explored by the robot and the vision component would be able to detect the object that was previously occluded by the flipper (see Figure 4).
Summary
In a dynamic, adverse environment such as USAR, a shared situation awareness is required and derived as a result of human-robot interaction. In this context a suitable interplay between supervised autonomy and full autonomy is needed. We have described the main features of a control system where HRI is fully based on a mixed-initiative planning activity that integrates the operator interventions with the robot activities. This control system allows us to define a set of hybrid operational modalities lying between teleoperated mode and autonomous mode that are crucial in a collaborative planning setting. The benefits of the mixed-initiative approach have been shown by focusing on the problem the morphological adaptation of a rescue robot with respect to particular tasks.

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References

