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Mobile Robotic Issues for Urban Search and Rescue

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Abstract: The paper considers three important issues in the design and utilisation of teleoperated urban search and rescue robot systems, namely localisation, locomotion and human-robot interfaces. Prototype systems are designed, developed and presented. For the localisation aspects a cost effective infrared beacon based system is presented for 2D applications. For the locomotion aspects a four-limbed adaptive articulated tracked vehicle is presented having the capability of changing its mode of operation to overcome large obstacles and move effectively in unstructured environments. For the human-robot interaction aspects, key user-centric metrics are proposed and investigated to assess the effect on overall system performance. The metrics considered are situation awareness, tele-presence and workload. Experimental results for all three aspects are presented.

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1. INTRODUCTION

Over the last few years mobile robots have started to be commonly used in many critical application domains considered to be dangerous for humans, such as military exploration and search and rescue missions. Their use in the service sector is predicted to be one of the most vital uses of robot systems. Despite recent advancements of artificial intelligence, robotic AI is still too immature to allow robots to autonomously co-exist with humans with reliable safety and task performance. Keeping the human in the control loop of the robot, particularly in decision-making processes, is much more efficient, safe and preferred by many end user groups, such as military or safety forces. A cooperative relationship between humans and semi-autonomous robots, in which one party complements the other's weaknesses can result in considerable improvements from the viewpoints of user-friendliness, overall effectiveness, safety, reliability, etc.

Some of the main issues that will have a significant impact on the performance of the human-robot teams regardless of the task are the following:

- Effective locomotion mechanisms
- Accurate simultaneous localisation and mapping
- Efficient and friendly human-robot interactions

Each one of these issues is examined in turn, and a case study solution for each, based on the work of the authors, is presented. Although the work was carried in different platforms, it should be considered as part of a unified project.

2. LOCOMOTION

Typical outdoor applications which need rough terrain locomotion capabilities are search and rescue robots, volcanic exploration robots, planetary exploration robots and military robots. Outdoor rough terrain typically includes rocks, sand, muddy water, rubble, drainage culverts, etc. Indoor rough terrain can include furniture, stairs etc. In a typical urban search and rescue environment a robot can also encounter rubble, debris, pipes, wires, etc. Despite all the extensive research and advances in robot locomotion, it is still currently impossible to build a robot that would be able to cope with all different kinds of terrain. Robot locomotion requires custom design based on the terrain requirements of the operating environment.

Many terrestrial locomotion mechanisms have been proposed and tested. Wheeled robots remain the most popular due to the ease of implementation. Wheeled locomotion varies from single wheeled gyro-stabilised machines like the Embrio Concept by Bombardier to two wheeled versions like the Segway Robotic Mobility Platform based on the Segway Human Transporter. However, these are mainly of academic interest as they can only move over benign terrain. Three wheeled robots like the popular Pioneer 3 are widely used for indoor applications but are not suited for rough terrain applications. Four wheeled robots like the Nomad by CMU are better suited for rough terrain applications. However, the most popular configuration for rough terrain uses among wheeled robots are the six-wheeled versions like Terregator, Robovolc, Shrimp Rover, Marsokhod and the NASA Rocker Bogie Series consisting of Spirit, Opportunity, Sojourner, Fido and Rocky 7. Legged robots range from the one legged ARL Monopod II, two-legged

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robots like the Honda Asimo, three legged PLIF devices, four legged Sony Aibo to the six legged AMRU5. However, due to their complexity and slow speed, legged robots are seldom used in practical rough terrain applications. Hybrid wheel-leg robots like the Wheeleg and the Whegs are another form of providing effective locomotion. However, they are not very effective in rough terrain applications. Tracked robots are perhaps the most popular for rough terrain applications. Famous examples include the Spike, Foster-Miller Talon, Matilda, RT-20 Unmanned Robotic Vehicle, MPRS/URBOT and the PackBot by iRobot.

Each of these categories of robots has a set of advantages and disadvantages. For example, wheeled locomotion is the simplest and easiest method to implement; however, it is not very effective in complex terrains. Legged locomotion can have better results in overcoming obstacles but it is more complex to design, it is currently not very reliable and often leads to robots with limited travel speeds.

2.1 Articulated tracked locomotion vehicle

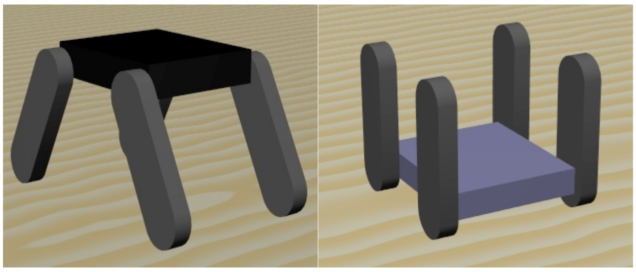

Fig. 1. The quadra-tracked locomotion system

Our aim was to design and construct a robot prototype that would be capable of traversing rough terrain similar to that found in urban search and rescue or military applications. The Quadra-Tracked Adaptive Locomotion Mechanism is based on four tracked modules that are individually articulated (Fig. 1). These make the locomotion platform highly adaptable to the terrain, thus giving it excellent rough terrain capabilities. Rotary position sensors are used to read the angular position of each track module.

The idea was that the robot would be able to change its configuration to mimic some successful but fixed locomotion mechanisms. As such the robot is capable of greater contact with the ground resulting in better traction when necessary, e.g. ability to climb up and descend down a slope without slippage or pass over a hole. By rotating the tracked modules, the locomotion system can adapt to give a higher ground clearance capability or better stability as the situation demands. This enables the robot to climb large obstacles as shown by the experimental results.

Locomotion Mode A (Fig. 2) is used when the terrain is extremely difficult to travel on and needed a lot of traction and ground contact like steep slopes, large holes, steps, etc.

Locomotion modes B and C (Fig. 3) are used in relatively smoother terrain. In these modes, the robot behaves like a wheeled robot with a classic bogie.

Mode D and Mode E (Fig. 4): Tracked robots like Matilda have a modified track design which enables them to climb over obstacles. Locomotion modes D and E enable the robot to behave similar to these robots.

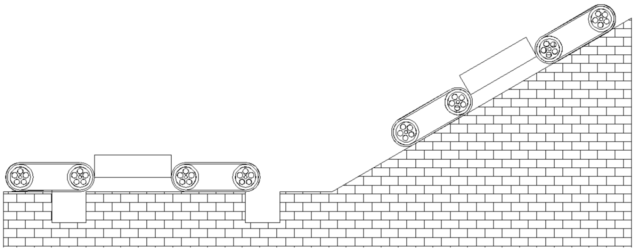

Fig. 2. Locomotion mode A

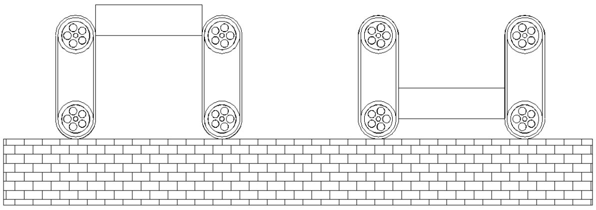

Fig. 3. Locomotion modes B and C

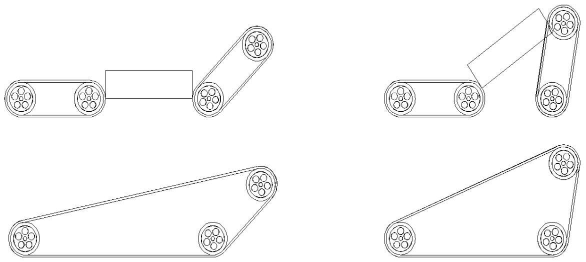

Fig. 4. Locomotion modes D (left) and E (right)

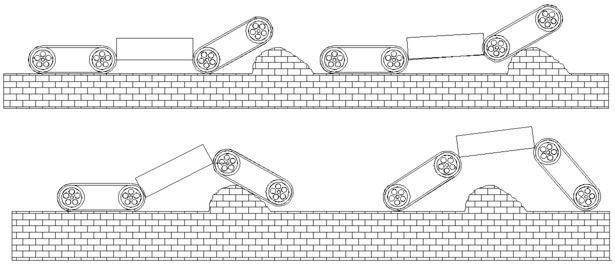

Fig. 5. Locomotion adaptability overcoming an obstacle

Fig. 5 illustrates how the robot can scramble over obstacles using its track articulation advantageously. This enables the robot to negotiate much larger obstacles than it would if it was using standard locomotion techniques, such as wheels or fixed tracks.

To test the performance of the Quadra-Tracked System, the NIST Red arena (Wang et al., 2003) was studied carefully and its key features were implemented in the test arena setup. The arena designed for testing the robot consisted of ramps, concrete blocks, strewn furniture, metal rods, pipes, bars, wire, plastic bags, gravel bed, steps, confined spaces etc. The robot could easily travel through this arena by utilizing its various locomotion modes and using reconfiguration of the tracks to scramble over the larger obstacles.

Currently the robot uses skid steering for maneuvering. This means that it is capable of turning on the spot but this strategy may not be the best for all terrains. The tracks help in maneuvering, especially over hard surfaces as the large treads on the tracks reduce the contact surface area and this reduces the frictional force that the robot has to overcome while turning. With the help of reconfiguring the tracks, the robot can climb over obstacles as high as $200mm$.

3. SIMULTANEOUS LOCALISATION & MAPPING

Self-localisation, i.e., knowing your position in a frame of reference, is a fundamental element for every task. Biological organisms use a variety of techniques in combination with various inputs from their senses, and they can localise themselves to a high degree of accuracy with impressive ease. Localisation can be applied on many levels, starting from knowing the position of the overall body of the robot, to the position of the individual modules, such as the position of each wheel, leg, gripper, etc. A frame of reference can be a local one, i.e., knowing your position in a room, and the global one, i.e., knowing your position within a bigger frame of reference such as in a building, a city, the planet earth, even the solar system, etc. These also have two forms, a relative one changing according to the robot's position, and an absolute one that is fixed to some standard reference frame. Depending on the mission requirements and the operating environments appropriate frames of reference are selected. A key issue is to design appropriate transformation matrices, although the majority of these have been resolved and the kinematics now well understood.

In the majority of cases it is sufficient for teleoperated mobile robots to know the position of the system. The prior knowledge of having a map of the operating environment can be a great help in some applications such as the case of shopping robots, it is not always that beneficial in search and rescue applications; here the robot has to face the "chicken-n-egg" problem, namely, in order to have precise localisation, a map is needed, and in order to build an accurate map of the environment, precise localisation is needed. This problem is commonly referred to as simultaneous localisation and mapping (SLAM).

Some techniques can provide the location of the robot independent of the knowledge available from a map. The simplest of all is dead reckoning using odometry data. This method is a typical example of relative localisation, as the position of the robot is deduced based on knowledge of the starting point and measurement of its movements. Other methods, collectively known as absolute localisation methods, rely on the perception of certain features in the environment to deduce the position of the robot, without the need for previous knowledge. One example of such methods uses RF, optical or acoustic beacons at known locations and triangulating to realise the position. Other methods are based on feature recognition in combination with probabilistic methods, e.g., asking the question "What is the likeliness that I would see what I see from being in this position?"

3.1 Indoor 2D localisation

The research presented here is aimed at realising indoor 2D localisation using triangulation. IR beacons have been selected because of their advantages over the other types. Specifically, RF beacons with even the most expensive antenna will generate a rather wide beam, introducing a margin of error in determining the pointing angle; this error in pointing is smaller in IR beacons. Optical beacons using landmark identification are computationally more expensive and have accuracy problems as landmarks may look similar. Furthermore, IR beacons prevent interference within adjacent rooms, as IR signals cannot pass through walls, IR receivers are small and highly directional requiring low power, there is no electromagnetic interference, the signal power can be easily reduced to cover smaller areas and they are cost effective as they use off-the-shelf components.

Simulations (with the Player/Stage robot simulator) and real world studies were conducted to identify the accuracy of triangulation using IR. The common problem with all three object localisation technique algorithms is the failure to localise the robot on or outside the circumference defined by the beacons. Also the three object localisation algorithm defined by Charles et al (1992) requires the beacons to be properly ordered. To overcome the above problems we used an improved version of the algorithm define by Esteves et al (2003). Using this algorithm the beacons can be placed anywhere in the plane provided that two beacons do not share the same location. Also the algorithm works over the whole plane, inside as well as outside the triangle formed by the three beacons, except for the few lines shown in Fig. 6.

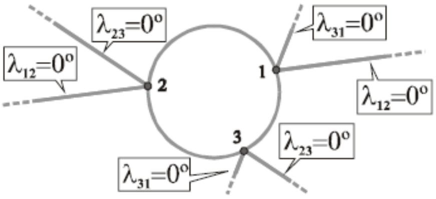

Fig. 6. Robot is unable to localise itself on the lines shown

The simulation experiments were carried out with a room size of $10m \times 10m$. To ensure accurate positions and orientations of the robot were obtained, the positions calculated using the odometry method were compared to the values obtained from the four beacons. Using different sets of three beacons it was possible to calculate different possible robot positions and average these to get some improvements in the localisation resolution. If any of the positions calculated were vastly different from that calculated using odometry, they were discarded. This approach safeguarded against failure of any beacon, that is, there was some redundancy in the system.

The resulting algorithm gave good accuracy with an error of $\pm 0.14\%$ in the robot's position (x, y co-ordinates) and a $\pm 0.7\%$ error in the robot's orientation. The increased error in the robot's orientation was due to the difficulty in determining the robot's pose using the simulation software. The actual robot's orientations, indicated by Player/Stage, were different producing the given error in calculating the robot's pose. This error can be minimised by using the latest version of the software, which also has a localised proxy inbuilt.

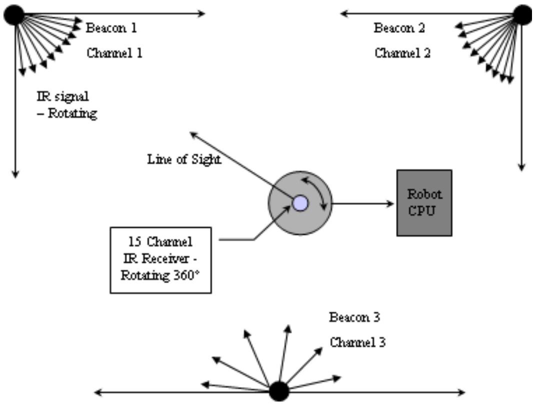

Fig. 7. Schematic diagram of the beacon system

The experimental setup is shown in Fig. 7. The IR beacon system was experimented in a room with an arena of $200cm \times 200cm$. The IR transmitters, used as the fixed position beacons, were configurable to 16 channels, allowing the use of multiple transmitters in one room. The transmitters had a range of $15m$ which could be easily calibrated for smaller room sizes. Also, in order to get the best line of sight the transmitting IR LEDs were shielded to provide a thin beam and hence get as precisely defined pointing angles as possible. The Receiver used on the robot was mounted on servo motor to detect the transmitted signals and was capable of detecting up to 15 beacons in one room.

The beacons were placed at fixed positions in the arena. The tests were validated by visually observing the actual robot's position with the ones calculated by the algorithm. Fig. 8 indicates the robot's actual position with the calculated results and Fig. 9 indicates the actual and calculated robot's orientation in the arena. The system showed a positional accuracy of 97.82% and orientation accuracy of 99.44%. The error of ±2.17% in position is caused by many factors such as finite width angle of the IR, positioning error of the beacons and calculation errors to deduce the position of the robot.

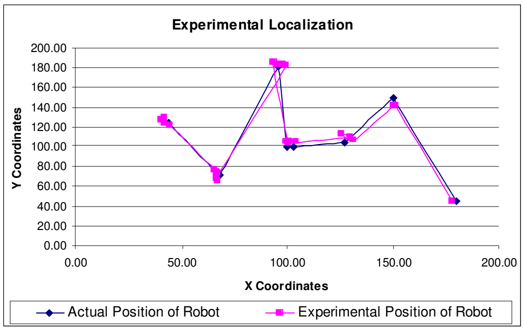

Fig. 8. Actual and calculated (x, y) robot positions

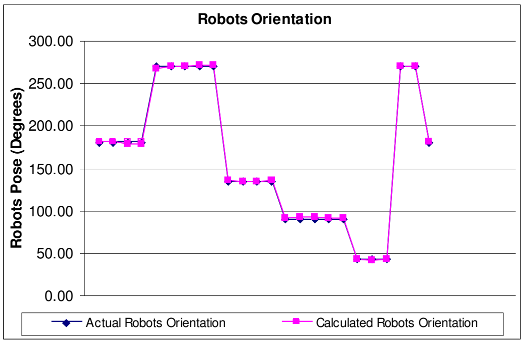

Fig. 9. Actual and calculated (x, y) robot orientations

The motor selected for the IR receiver was a servo with a gear mechanism to make it rotate by 360°. This reduced the least count of the system. If the system accuracy is to be improved, a stepper motor or a servo motor could be used to give a lower least count and hence a more accurate reading of the angle. Also the accuracy can be improved if the viewing angle of the IR transmitter is reduced by using narrow beam IR LEDs. The positioning of the robot and the beacons in the arena was done manually thereby adding further human errors into the localisation system.

Angle measurements from the robots between infrared beacons provide an accurate and viable method for localising robots indoors. The technique is scalable, accurate with very little hardware required at both the beacon side and the robot. The only limitation in using IR beacons is the requirement for line of sight. To alleviate this problem, beacons could be placed at high positions next to the ceilings (Nasipuri and Najjar, 2006). Including dead reckoning can further improve the accuracy of the method. The system providing high positional and orientation accuracies showing that IR beacons can provide accurate, low cost and easily implemented method for locating mobile robots. Such a method can be used in a variety of situations as the beacons can be placed in advance where allowed, or dynamically by the robot itself.

4. HUMAN–ROBOT INTERACTION

Regardless of the task whenever a human has to team up with a robot to accomplish a task there is a need for user-friendly, dynamic and effective means of human-robot interaction (HRI). The classic design of HRI systems so far has been taking into account the robot system itself thinking that the end user needs to have powerful and flexible interfaces. However, the interfaces can become rather complex as well as rely on the assumption that the user has a deep knowledge of the system like the system designer. As a natural result, most HCIs have failed to produce user-friendly and effective interfaces for the robot systems developed to date.

As such, a more user-centric approach is needed to include human-centric design elements rather than robot-centric ones. Such human-centric issues are situation awareness (SA), telepresence (TP) and task workload (WL) (Burke, et al., 2004; Gatsoulis and Virk, 2007). While the latter two (TP and WL) have been extensively researched for years they still remain active fields of research with more questions than answers as systems become more complex. SA on the other hand is an element that has recently caught the attention of the research community, due to the speculation that good SA will result in better task performance (P). Although, SA research is relatively new in robotics it has been a central area of research in avionics and air-traffic management. The air traffic area in particular shares many similarities with teleoperated robots; these include the fact that there is an operator of a complex system with interaction interfaces through which he tries to coordinate and control multiple semi-autonomous agents to achieve the required tasks. As such, it has been strongly suggested that the lessons learnt in the air traffic management sector should be transferred into the robotics domain (Adams, 2002). Despite the extensive research there are still many open questions and new theories and assessment methods being developed. In fact, there is no clear consensus on whether SA is a causality of good performance or, rather a natural and automatic process (Flach, 1995). Independent of its form, SA has been hypothesised to guide decision making. Of course, there are other human-centric factors that influence task performance, e.g. formal training and experience of the operator, however, these are issues that the system engineer does not have control over. On the other hand the systems and the interaction interfaces can be designed on the basis of how well they support the human factors of SA, TP and WL.

Providing an extensive review of the theories behind these issues and the details of the individual methods are beyond the scope of this paper. However, in order to better understand the main issues and the case study that follows, a theoretical base and some definitions must be provided.

Workload can be defined as the amount of processing resources that the user has to allocate for the completion of the task or to maintain an adequate performance. The pool of available resources though is not infinite. There is a point that the user becomes burnt out, which results in degraded performance. Workload is considered to be a multi-dimensional aspect. For example SWAT (Reid and Nygren, 1988), a method for measuring Workload, distinguishes between the following self-explanatory dimensions: time demands, effort of the user and level of stress experienced.

Telepresence has been defined as perceiving the remote environment as if physically there (Sheridan, 1992). Such a definition signifies an element of “naturalness”. According to Witmer-Singer (1998) telepresence is an indication of involvement. Combining these two, it can be said that from the system designer’s point of view, telepresence signifies the quality of the interaction interfaces in terms of naturalness and involvement.

Situation awareness is the mental representation of the agent itself, the objects around it, the mission goals, how all the elements evolve, etc. The main research issue to be addressed needs to answer the simple question: “What is the current situation and how will it evolve in the future?” Lack of or poor levels of SA, has often been identified as the main cause of human error. According to one popular theory (Endsley, 1995) this is a three stage process, namely: perception of the data, comprehension of the data into meaningful information, and prediction of the future states.

4.1 Influence of human factors to task performance

Naturally, there are many issues to be resolved, such as “What is the relation of these factors with performance?”, “What measurement methods are appropriate for each?”, “What would be a good prediction model of performance based on these?”, etc. The results presented here aim to investigate the first question, i.e., “What are the relations between them?”

For this, an experimental study was utilised, involving a simulated robot urban search and rescue (USAR) scenario. Seventy subjects were recruited, out of which thirty-three were potential end users, including a USAR task force and a unit of paramedics. The rest were academics and fellow research colleagues. Although none of them had prior experience with performing robot teleoperation tasks, training was provided prior to the experiments. The scenario consists of the following mission: “In the search and rescue operations of the aftermath of a natural disaster, the ground floor of a building has been classified as too dangerous for human personnel to enter. A robot is to be used to search the interior of the building and the operator has about 30 mins of operational time to search the building for possible casualties and bring the robot back to the exit point. During the mission the operator must protect the robot and mark the position of the casualties.”

Due to space restrictions it is only possible to present only a brief overview regarding the measurement methods used. Workload was measured post-experimentally using a heavily modified version of SWAT (Reid and Nygren, 1988) as the original version of it proved to be rather complicated and time consuming. It assumes that workload is a factor of time demands, effort of the subject and stress experienced. Telepresence was also measured at the end of the experiment using a new questionnaire based on the ideas and measurement methods developed by Witmer and Singer (1998) and Slater et al. (1995). The main dimensions measured are the involvement and control of the subject, naturalness of the task and the quality of the interaction interface. Lastly, situation awareness was measured using two methods based on two common sets of dimensions. The first one represents Endsley (1995)’s views of situation awareness, that it is a factor of three levels, these being, perception of the data (Level 1), comprehension of it into meaningful information (Level 2) and prediction of future states (Level 3). The second level includes the dimensions of mission awareness which is concerned with the goals of the mission, time awareness concerned with the time issues of the task and spatial awareness concerned with the spatial issues of it. More information is presented in Gatsoulis and Virk (2007). The first measurement method was developed mainly based on Endsley’s SAGAT measurement method, and as such it is applied during the task. The second one is applied retrospectively and aims to measure the level of situation awareness of the subject throughout the complete duration of the task.

Extreme cases were removed from the dataset leaving a sample size of sixty three cases. Pearson correlation coefficients were calculated to identify the effect of each factor to the performance. Table 1 summarises the results and situation awareness seems to be highly correlated with performance and seems to be explaining about 40% of the variance in it. This means that an accurate mental model of the situation is necessary for effective decision making. Telepresence and workload also seem to have a medium effect, with the first one accounting 17% and the latter 7% in the variance of performance. These mean that as the subject gets more involved into the task the better his/her performance is. Overall these three variables seem to be the main factors influencing performance as they explain 64% of its variance. Another important correlation that appears to exist is that between situation awareness with telepresence. This means that the more involved the subject gets into the task, the better the mental model he/she has about how the situation is. On the other hand, workload has a negative effect on situation awareness. This means that the process of forming and maintaining a good level of situation awareness is high in mental processing demands, and therefore when they are not available the subject is finding it difficult to maintain an accurate mental model of the situation. Lastly, telepresence and workload seem to have a very small correlation with each other. This is surprising, as it was expected that as workload increases then the subjects would become more distracted breaking his/her involvement from the task.

Table 1. Pearson correlation coefficients

	P	SA	TP	WL
P		.629⋆	.412⋆	−.311⋆
SA	.629⋆		.500⋆	−.407⋆
TP	.412⋆	.500⋆		−.141
WL	−.311⋆	−.407⋆	−.141	

⋆ significant at .01 level

The results presented here indicate that all three human factors of situation awareness, telepresence and workload are important design issues that affect task performance of teleoperated robots. As such, they should be taken into account by system engineers when designing human-robot interaction interfaces. Furthermore, HRI issues are necessary and applicable for effective, reliable, easy to use and hence successful use of robots, regardless of the robot platform and its capabilities. Finally, the results presented here indicate that there are a complex and dynamic relations between the variables, and further analysis is needed. The individual effects of each of the dimensions are also a further issue for investigation. This is important as it will reveal specific requirements for effectively carrying out a task, benefiting system designers by knowing where to focus their efforts.

5. CONCLUSIONS

The paper has considered some key issues in the design and utilisation of teleoperated urban search and rescue mobile robot systems; these issues relate to having effective locomotion and localisation strategies for the operational environment. In addition, as most urban search robots are utilised remotely it is important to design effective human interfaces so that the human operator can be supported to perform the search tasks. The performance of the human operator in carrying out these tasks is studied with respect to three key performance metrics, namely situation awareness, tele-presence and workload. The paper has presented experimental results for all three aspects.

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