Methodology of Control and Supervision of Web Connected Mobile Robots with CUDA Technology Application

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Abstract:

The main problem of the following paper is control and supervision of web connected mobile robots. Taking up this subject is justified by the need of developing new methods for control, supervision and integration of existing modules (inspection robots, autonomous robots, mobile base station). The methodology consists of: multi robotic system structure, cognitive model of human supervisor structure, system algorithms and cognitive model algorithms. The research problem comprises web connected mobile robots system development structure with exemplification based on inspection-intervention system. The modelling of human supervisor's behaviour is introduced. Furthermore, the structure of a cognitive model of human supervisor with the application of the new NVIDIA CUDA technology for parallel computation is proposed. The results of experiments performed in real, virtual and hybrid environments are discussed. The methodology is verified by exemplification based on a system composed of autonomous mobile robot ATRV Jr and robot INSPECTOR.

Keywords: mobile robot, cognitive control and supervision.

1. Introduction

The main problem undertaken in the paper is control and supervision of web connected mobile robots, for example, inspection intervention robot system, with an application of CUDA technology. The main applications of multi-robot inspection intervention system are actions in a disaster area, covering all the consequences of fires, chemical hazards, and the effects of terrorist attack. The environment of the system forces short time of inspection, and determines basic goals for the system. This provides clearly defined working conditions, the criteria for checking correctness of control and supervision algorithms and the position for dissertation on the background of existing knowledge.

Many studies have shown extensive technical development in the area of mobile robotics. There have been many solutions [8] for technical issues related to unique mechatronics designs of mobile robots. Many new robots have high mobility [31] in difficult terrain. In addition, number of robots equipped with sophisticated sensors [32] increases, which enhances the effectiveness of search and detection of victims [11],[33].

2. Multi robotic system structure

The main object of research in this work is a web connected mobile robot system, for example, the inspec-

tion - intervention system consisting of a mobile base station, a group of autonomous robots and remote-controlled robot, equipped with a manipulator with n degrees of freedom. Figure 1 shows structure of such a system.
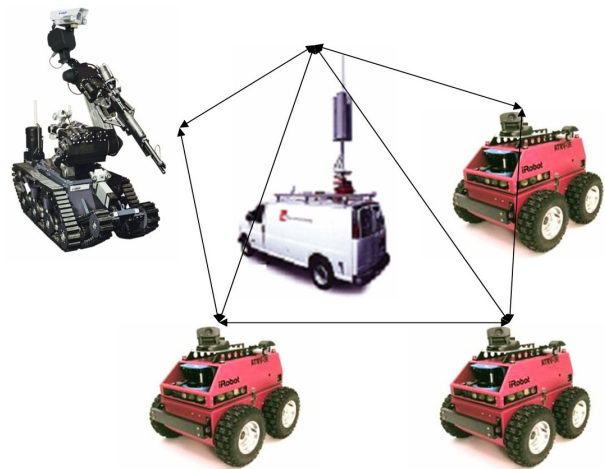

Fig. 1. Inspection intervention system.

The main tasks of the system is an inspection and intervention of hazardous environment for human activities. The system consists of three following components: mobile base station, the remotely controlled robot, autonomous mobile robot.

2.1. Mobile base station

It provides information concerning the robot's environment to the operator. The station is equipped with HMI software using advanced techniques of interactive graphics for operator interaction with robots. An important problem for the operator is a large quantity of information provided by the robot sensors, which can result in a problem with making quick and accurate decisions. During the routine work the system should assist the human operator, which will ensure proper operation despite operator's errors. For this purpose, a cognitive model of human supervisor is proposed, which solves some of the above-mentioned problems.

2.2. The remotely controlled robot

It is aimed for inspection and intervention disaster area. The robot is equipped with a video cameras, a manipulator with n degrees of freedom and communication system. The robot is able to partially replace the human in the environment that affects the health or even threatens human life.

2.3. Autonomous mobile robot

Its task is the inspection of the area of the disaster. For this purpose it is equipped with a laser measurement systems that provide 3D data of the environment, video camera, ultrasonic sensors for obstacles avoidance, local position system determining robot position. Robot can be, depending on the application, additionally equipped with chemical sensors or thermal camera.

From the standpoint of the system of web connected mobile robots there may occur a crisis situation that may lead to mission failure and even robots damage. For the purpose of this work crisis is an exceptional situation, which is interpreted by supervisor as a state of dangerous, potentially threatening the performance of the mission or the safety of the system. Developed cognitive model of human supervisor is characterized by supervising the robot system showing similar reaction as human, in the event of an emergency. Therefore it has the ability to recognize emergencies and the ability to generalize during making decisions, it is able to control the robots in a way similar to human.

3. Cognitive model of human supervisor

Developed cognitive model of the human supervisor is working with a distributed control system of mobile robots and has developed perception, which forms the basis of knowledge. Figure 2 shows the model diagram.

Due to the potential loss of communication between the main inspection - intervention system components developed and implemented distributed cognitive model of the human supervisor of the robotic system is combining the elements of a centralized system and multi agent system. Figure 3 illustrates the idea of the model.

Multi agent cognitive architecture of the developed cognitive supervisor consists of three layers. The first layer is reserved for the most important in the hierarchy of agents - the cognitive supervisor of the robotic system. In the absence of communication problems the cognitive model works in a centralized system scheme, where agents from the lower layers, are fully subordinated to the execution of his orders. From the perspective of software engineering in this case we are dealing with a distributed implementation of a single cognitive supervisor. Otherwise, if there are communication problems between layer I and layer II or within layer II, the agents from layer II are fully autonomous and operate in a pattern of multi agent system. It should be noted that fault-free communication between the agents of layer II and layer III is assumed, as a result of using wired Ethernet communications. Cognitive architecture is strongly conditioned by supervising multi agent system where CSRS is installed at the base station, CSR1, CSR2, CSRn are installed on a mobile robot on-board computers, and coordinate the work of sub-CS1, CS2, CSn, which in turn, are installed on computational units of the robot, overseeing the work of operating systems. Additionally, in the architecture in Figure 3 CSRCR is an agent supervising the remote-controlled robot, assuming that the robot is equipped with a suitable on-board computer.

3.1. Cognitive map

Cognitive map is a result of the sum of observations made with the use of robot perception. Cognitive map is a source of information for the cognitive model, it stores the state of the system, including robots, the environment and mission. On this basis the cognitive model of human
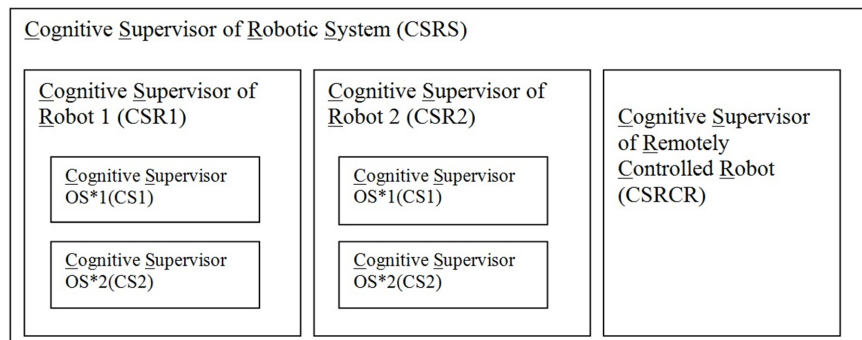

Fig. 2. Scheme of the distributed cognitive supervisor of the robotic system.
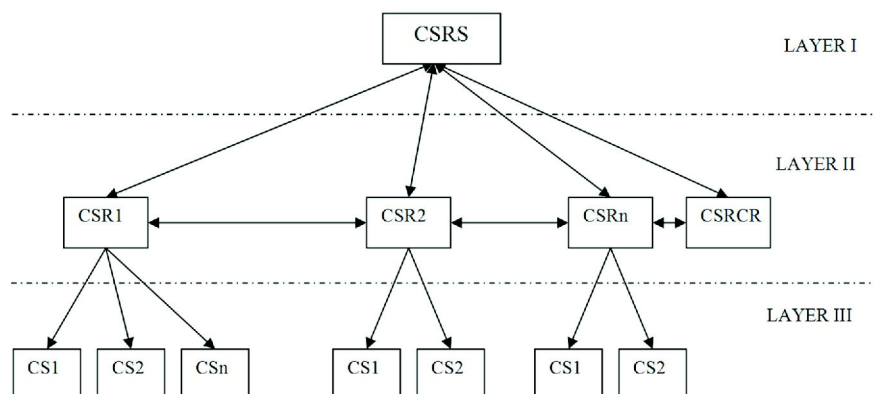

Fig. 3. Scheme of the distributed multi agent cognitive supervisor of the robotic system.
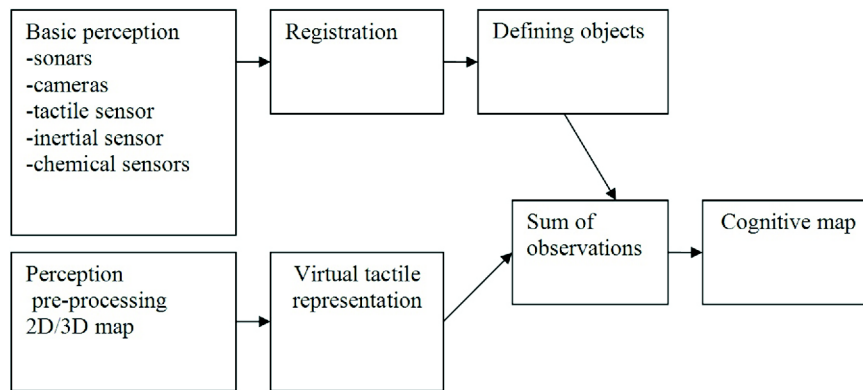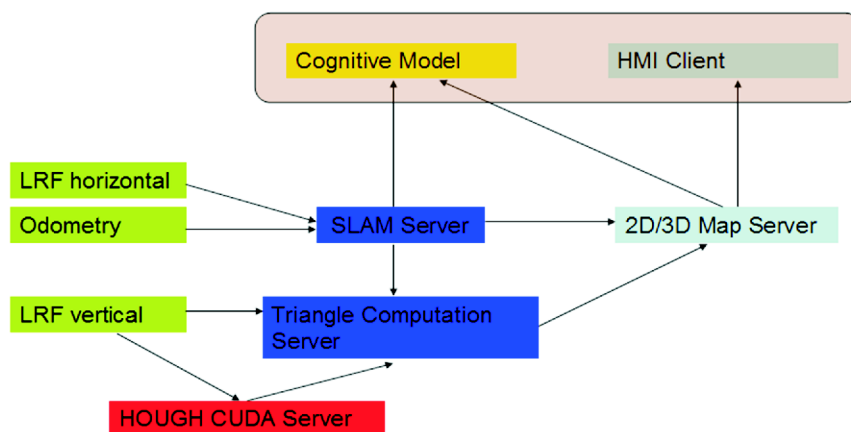
Fig. 4. Scheme of cognitive map building.

Fig. 5. 2D and 3D maps available for the cognitive model and the operator.

supervisor is able to detect danger and possibly intervene. The result of perception, including receiving information and processing, and then thinking in terms of transformation of this information, is the cognitive map (Figure 4). Cognitive map can be assumed as some form of description of the world. On the basis of sufficient information about the world cognitive model may decide to effect behavioural or cognitive. Behavioural effect is directly associated with making a particular action (following path movement of the robot), while the cognitive effect creates new structures, which in terms of machine learning can mean the extension of the decision tree, or creating a new rule-making, and for the monitoring of the emergence of the mission new graph of the mission.

3.2.   Cognitive map building algorithm

From the standpoint of implementation the cognitive map is a sum of observations obtained by means of robot perception, in a form understandable to the cognitive model of the human supervisor. Cognitive model makes control decisions based on the cognitive map. The cognitive map building algorithm is implemented to obtain the map model that is understandable at the same time by the operator and by the cognitive model. It is assumed that cognitive model controls and supervises the system based on the same information as human does. The following elements are a part of the implemented perception of cognitive model:
- position of robots,
- configuration of a remote controlled robot arm,

- 2D/3D maps,
- map of temperature,
- map of chemical contamination,
- path,
- goal (position, time).

Robot position is determined by the robot positioning system. Information about the configuration of a remote-controlled robot arm is provided in binary form, where the logical value of 1 means that there may be a conflict of individual degrees of freedom of robot arm, while the value of 0 means the contrary. Map with obstacles is represented by a 2D raster map, where cells take values from 0 to 255, which corresponds to a probability of occurrence of obstacles in this space. 3D map is represented by a set of 3D points, a set of lines and a set of triangles. The figure 5 shows the implementation of the 2D and 3D maps, available for both, cognitive model of human supervisor and operator (HMI client).

The most important element in the implementation of the map is the SLAM (Simultaneous Localization and Mapping) algorithm. SLAM delivers the information concerning occupancy grid map with obstacles and robot position. To obtain 3D data robot has to move forward or rotate, therefore the data are collected from vertically mounted laser measurement system. The result is 3D cloud of points. From this cloud of 3D points the lines are extracted slice by slice using following algorithm with support of CUDA parallel computation:

1. transformLaserScanToCartesian( )
//procedure for converting the coordinates of points (r, a) into coordinates (x, y)
2. for each point
3.   for each point
4.   calculateLineParams
// parameters A, B and C for the line $Ax + By + C = 0$ passing through each pair of points
5. for each line
6.   for each point
7.   calculateDistancePointToLine( )
8.   sumIsPointCloseToLine( )
// for each line, for each point calculate the distance of a point from the line
9. while done
10. sortLines( )
// sort lines according to their number of points lying on the line within a certain distance (2 - 3 cm)

Steps 2, 3, 4 and 5, 6, 7, 8 are implemented using CUDA parallel computation. Double loops are executed in parallel, where each of the calculation (i, j) corresponds to one kernel in GPU. Based on the location of the robot and the two subsequent measurements of the laser the triangles are calculated in 3D space. The Figure 6 illustrates the idea of combining two lines in order to appoint the triangles.
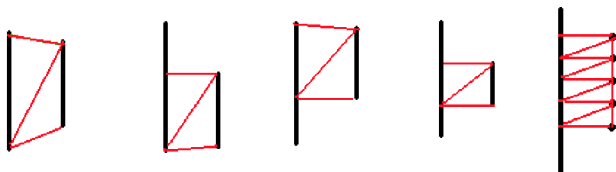

Fig. 6. The idea of an algorithm combining two lines to determine the triangles.

Full information about the cloud of 3D points, 3D lines and triangles are stored in the server 2D/3D Maps. HMI main program, as well as distributed cognitive model has access to the server through the CORBA interface, therefore it can be the core information for decision making module. Chemical concentration and temperature maps are provided in the same form as the 2D map, where different cell values correspond to temperatures in the area, or chemical concentration, scaled according to the adopted criterion. The goal is defined by a point on the map and the amount of time needed to achieve it. Planned path is a list of goals. In the case of a patrol task we are dealing with a graph, in which there is a cycle connecting the end with the initial goal.

4. Parallel approach with CUDA

CUDA technology is used in many fields of science for so-called, advanced scientific computing [20], [12]. Main applications are related to image processing [36], [34] or compression [30], segmentation [25], [35], edge detection [21], stereovision [15], motion tracking [17]. Significant use of CUDA is evident in studies of new algorithms in the field of graphs   including the shortest path algorithms [24], and Voronoi diagrams [22]. From the perspective of a significant acceleration of computing, CUDA is used in the calculation of grouping [9],[14],[37]. Referring to the

issues of artificial intelligence, a number of performed studies was related to neural networks [13],[18], face recognition algorithms [28], or speech recognition [27]. CUDA is widely used in interactive computer graphics [7], or 3D reconstruction [9], [26], [29]. It is noteworthy that areas such as cryptography [23] also benefit from CUDA's power of computing. CUDA application begins to have value in effective methods of inspection of implementation correctness of products such as: inspection of the correctness of the TFT-CCD [10].

CUDA was used for parallel computation in following tasks:
- ray intersection for obstacle avoidance with 3D map built in real time,
- 3D map building and reconstruction,
- internal procedure of classification process,
- line extraction from laser data,
- simulator of laser measurement system working in acquired 3D map.

5. Implementation of the autonomous behaviour of mobile robot

ATRVJr autonomous mobile robot equipped with sensors capable of detecting the environment is responsible for providing this information to the mobile base station. The system was designed in a distributed architecture, so it has the ability to run multiple tasks simultaneously. At this stage, due to lack of enforcement mechanisms to interfere with the working environment, cooperation of robots is the aggregation of information from sensors and delivering them to the mobile base station. The following illustration shows a diagram of elements of the autonomous robot behaviour, on the example of implementation of robot ATRVJr.
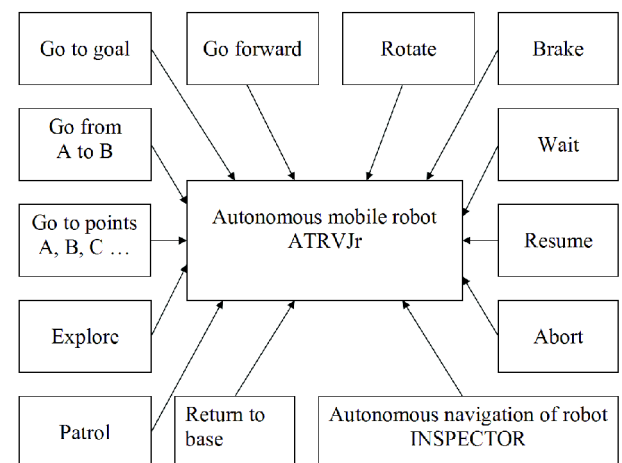

Fig. 7. Autonomous behaviours of ATRVJr robot.

Blocks "Go forward", "Rotate", "Brake" represent the low level autonomous behaviour. All the above structured algorithms for moving the robot are constructed with these blocks. Blocks of "Wait", "Resume", "Abort" represent the functionality to allow interaction with the algorithm that is currently executed. Blocks "Go to goal", "go from A to B", "Go to points A, B, C" carry out the task of moving the robot along defined path. Block "Explore" performs the task of visiting all the areas of defined map, the robot performs the task in two ways, first is chaotic

navigating on the map, the second is to use a graph algorithm to visit all vertices in a graph representing the environment. Block "Patrol" performs the task of patrolling a defined area on an ongoing basis until the execution of another order. Block "Return to base" performs the task of returning the robot to the base station. Block "Autonomous navigation of robot INSPECTOR" performs the task of autonomous control of the robot INSPECTOR to move it to a place where communication with the base station is restored. Obstacles avoidance is obtained through the implementation of the sliding window algorithm. The following illustration shows three types of binary maps (SLAM, inertial sensor, an area with a high temperature) that are used for sliding window computation. A summary binary map is showing all obstacles.
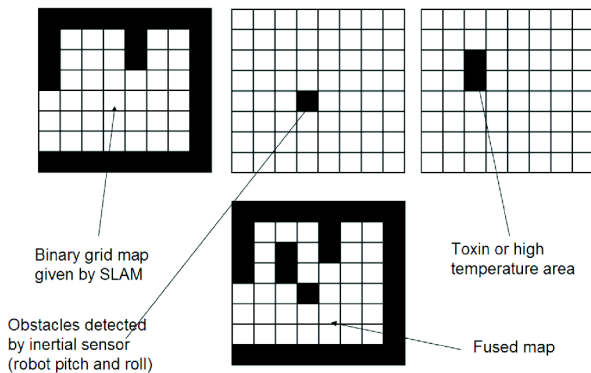

Fig. 8. The idea of building a binary maps based on maps SLAM, with the inertial sensor or temperature sensor.

The autonomous mobile robot can generate a path using the A* algorithm based on given binary map representing the obstacles.

6. Experiments

Verification of the methodology for control and supervision of web connected mobile robots was done on the basis of real inspection intervention system View-Finder [2], [4], [5], [6]. The test system includes ATRVJr autonomous mobile robot and a remote-controlled inspection robot INSPECTOR. There were also tests carried out using the Augmented Reality system AR [3] consisting of a real robot ATRVJr and virtual model robot INSPECTOR. Cognitive aspects were tested during cognitive map building and autonomous mobile robot navigation with obstacle avoidance supervision.

6.1.   Mission planning supervision

Mission planning is performed using the HMI that visualizes cognitive map. In this particular experiment the cognitive map is composed with 2D map, 3D map (generated based on actual measurements during the robot task), the position of the robot, defined objective and distance measurements of the robot sensors. Figures 9 and 10 present experiment connected with the monitoring of planning mission defined by the operator. The operator has the ability to define new goals with new position, visualized using flags. Cognitive information determines the collision-free path to the next goal.
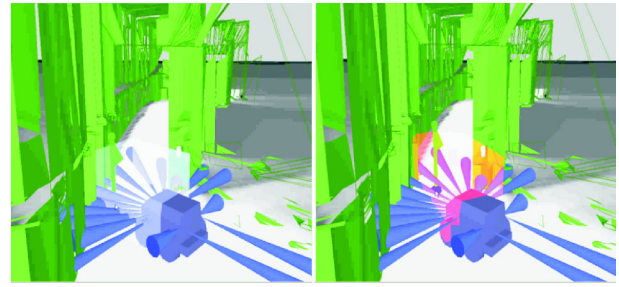

Fig. 9. Defining the goal by operator supervised by a cognitive model. On the left the colour blue means a collision-free path, the right colour red indicates a potential crisis situation.
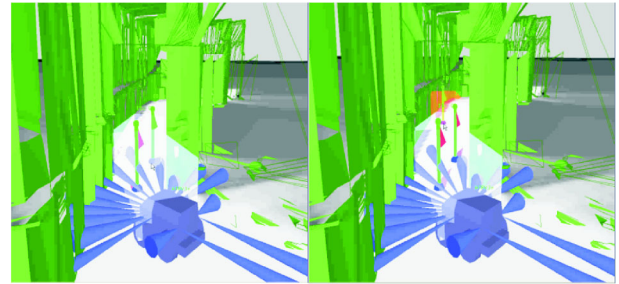

Fig. 10. Defining further goals by the operator controlled by cognitive model. On the left the colour blue means a collision-free path, the right colour red indicates a potential crisis situation.

The supervision of the operator's action of new goal definition is done in real time. In case of operator error that can lead to a crisis situation, cognitive model does not allow the operator to set such a goal.

6.2.   Inspection robot supervision

Figure 11 shows defined rectangular prisms, which contain robot main components.
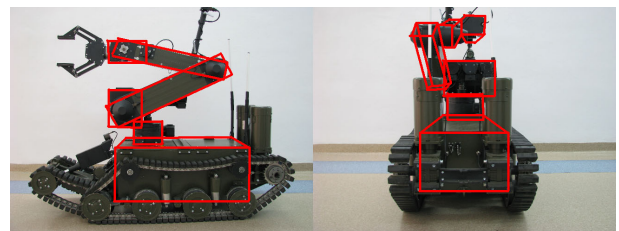

Fig. 11. Defined rectangular prisms which contain main components of INSPECTOR robot.
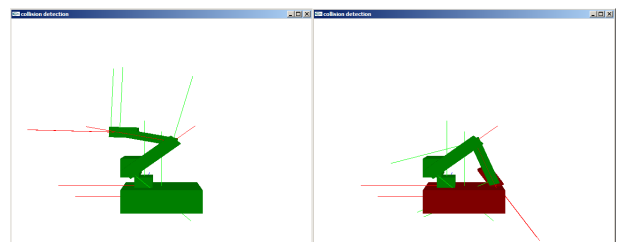

Fig. 12. The result of remote controlled robot supervision.

From the standpoint of the operator or cognitive model of human supervisor, it is essential to detect potential intersections between two rectangular prisms in the 3D robot model. Such an event is defined as a crisis. The task

of the operator, or a cognitive model, is to prevent damaging the mobile platform. Figure 12 shows a situation of crisis in the robot control (red colour).

6.3.   Inspection system testing

Correctness of the work of the inspection system, controlled and supervised by a cognitive model of the human supervisor was evaluated using AR technology (Augmented Reality [16]). Figure 13 shows a virtual model of the robot INSPECTOR used for experiments.
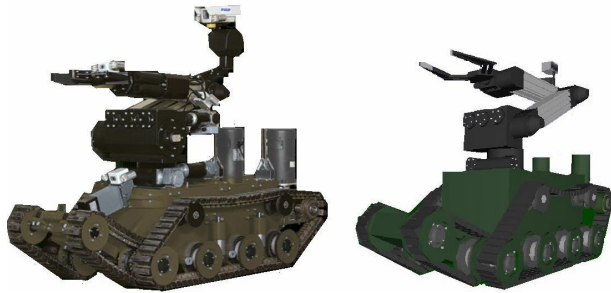

Fig. 13. INSPECTOR real robot and its virtual counterpart.

AR system consists of the following modules:
- real robot ATRVJr,
- real base station,
- virtual robot INSPECTOR,
- distributed cognitive model of human supervisor.

The experiment scenario is given:
1. Initially INSPECTOR and ATRVJr are in an unknown environment, lack of communication with the robot INSPECTOR.
2. ATRVJr: build a 3D map when moving to the goal.
3. ATRVJr: return to the starting point keeping safe distance from the robot INSPECTOR.
4. Cognitive model: control ATRVJr to the goal, while remote control (autonomously) robot INSPECTOR.
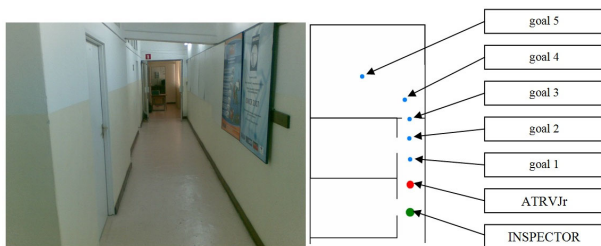

Fig. 14. Real environment of robotic system.

Autonomous mobile robot in the first phase of the experiment is building 3D model of the environment while it moves from the goal No. 1 to the goal No. 5. The Figure 15 shows the cognitive aspect - the effect of the 3D map building algorithm in real time, on the basis of the actual measurement delivered by a laser measurement system. In the next phase of the experiment an autonomous mobile robot returned to the position specified by the goal No. 1, cognitive model starts remote control of robot INSPECTOR, using the robot ATRVJr onboard computer. Figure 15 provides a view of the main HMI visualizing cognitive map associated with this particular experiment.
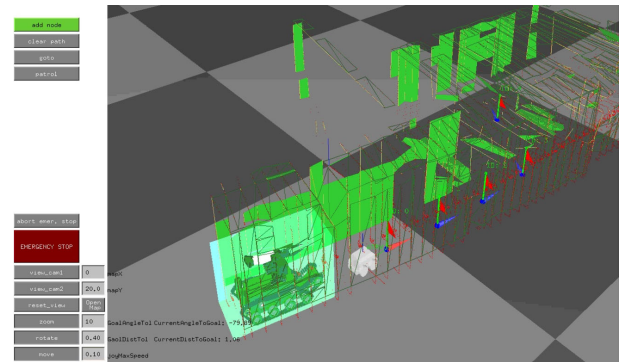

Fig. 15. HMI view of the cognitive map associated with the experiment.

Figure 16 shows crisis situation of the autonomous control of a remote controlled robot INSPECTOR. When a collision occurs between the surrounding rectangular block of INSPECTOR robot with an obstacle, cognitive model performs control correction in order to avoid the obstacles.
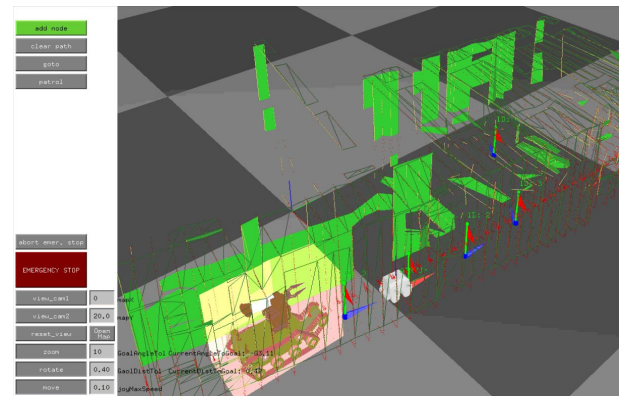

Fig. 16. Effect of collision detection between the rectangular prism surrounding the robot INSPECTOR and a 3D map-based on autonomous robot ATRVJr measurement.

Presented experiment confirms the correctness of the methodology of control and supervision of web connected mobile robots using CUDA technology and the correct operation of the system in terms of resilience to crises, caused by operator error. It should be noted that the ability to make correct decisions associated with the loss of communication between system components was positively verified. In this example the lack of communication between the base station and the robots was tested.

6.4.   CUDA algorithms computational complexity

The algorithms were verified based on the time complexity. The study was performed using five computer units of different configurations of CPU, GPU, RAM. The results for the unit of IntelCore 2 2.4 GHz, GF 1600M Quadro are interesting because of the possibility of installing the computer directly on the mobile robot. The results were organized in the following tables.

The experiments verify the cognitive model's response time which is comparable to the human response in a given situation. For example, cognitive model implemented in the weakest testing PC machines needs 30 ms to detect a crisis situation. In the case of a robot INSPECTOR,

Table 1. *The ray intersection algorithm with a set of 102,400 triangles.*

CPU	GPU	RAM	Time[ms]
Intel Core 2 - 2,4GHz (Mobile Workstation)	GF Quadro 1600M	800MHz	2,67
Intel Core 2 - 2,2GHz	GF 9800GX2	800MHz	1,79
Intel Core 2 - 3,0GHz	GF 3700 QUADRO	800MHz	1,45
Intel Core 2 Quad Q6600 - 2.4GHz	GF 8800 GTX	800MHz	1,17
Intel Core 2 Quad - 3.0GHz	GF280, GF280 (SLI)	1600MHz	0,52

Table 2. *Algorithm for the simulation of laser measure-ment system (181 beams of measurement) in the scene of 102, 400 triangles.*

CPU	GPU	RAM	Time[ms]
Intel Core 2 - 2,4GHz (Mobile Workstation)	GF Quadro 1600M	800MHz	520
Intel Core 2 - 2,2GHz	GF 9800GX2	800MHz	360
Intel Core 2 - 3,0GHz	GF 3700 QUADRO	800MHz	280
Intel Core 2 Quad Q6600 - 2.4GHz	GF 8800 GTX	800MHz	230
Intel Core 2 Quad - 3.0GHz	GF280, GF280 (SLI)	1600MHz	100

Table 3. *The average response time of the cognitive model of the mission planning monitoring, 102,400 triangles.*

CPU	GPU	RAM	Time[ms]
Intel Core 2 - 2,4GHz (Mobile Workstation)	GF Quadro 1600M	800MHz	30
Intel Core 2 - 2,2GHz	GF 9800GX2	800MHz	13
Intel Core 2 - 3,0GHz	GF 3700 QUADRO	800MHz	11
Intel Core 2 Quad Q6600 - 2.4GHz	GF 8800 GTX	800MHz	9
Intel Core 2 Quad - 3.0GHz	GF280, GF280 (SLI)	1600MHz	5

Table 4. *Algorithm line extraction from the measurement of laser measurement system (181 points).*

CPU	GPU	RAM	Time[ms]
Intel Core 2 - 2,4GHz (Mobile Workstation)	GF Quadro 1600M	800MHz	522
Intel Core 2 - 2,2GHz	GF 9800GX2	800MHz	477
Intel Core 2 - 3,0GHz	GF 3700 QUADRO	800MHz	380
Intel Core 2 Quad Q6600 - 2.4GHz	GF 8800 GTX	800MHz	310
Intel Core 2 Quad - 3.0GHz	GF280, GF280 (SLI)	1600MHz	180

control algorithm respond occurs no later than after 60 ms [1]. The conclusion is that the cognitive model needs about 90 ms to make a decision. Concerning the 100 ms communication constraints, the cognitive model does not affect the work of commercial mobile robot.

7. Conclusion

The result is a new methodology of control and supervision of web connected mobile robots using CUDA technology. This is a new approach that can be applied in the inspection multi robot systems for anti-crisis assistance. Conducted experiments on a specific example of the multi robot system show the ability of developed algorithms to control and supervise various types of mobile units. Specific conclusions are as follows:

- in the multi robot system there are autonomous agents that can operate independently in the event of loss of communication with other agents of the system, while being supervised by a distributed cognitive model of human supervisor,

- human supervisor is modelled with accordance to cognitive philosophy, where model of perception and the ability to learn how to control robots were developed,

- as a result of emulating way of thinking of human supervisor in decision making, implemented cognitive model of human supervisor is able to react appropriately in emergency situations, by recognizing the crisis and appropriately controlling the robots,

- proposed distributed cognitive model of the human supervisor combines a hierarchical structure with distributed and thus gave the supervision process resistance to communication problems in the network of robots,

- implemented new algorithms using CUDA architecture to increase the functionality of mobile robots,

- developed new HMI programs in a more intuitive way transmit information from robots and make it possible to control them with the use of interactive graphics, and consequently may increase efficiency of the operator.

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