RoboCup Rescue 2016 Team Description Paper MRL

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Info

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https://to-be-announced.org

***Abstract*—This paper introduces a new package of robotic systems for rescue operations. Particularly, a new advanced autonomous robot and a tele-operative robotic system with dexterous manipulator for different rescue missions have been designed and implemented. These robots will operate as a practical system to assist rescue personnel in real disaster situations such as earthquakes and explosions. The main capabilities of the system software are simultaneous localization and mapping, navigation, collision avoidance, sensor fusions, victim detection and exploration. Moreover, the robotic systems are developed on a set of sophisticated mechanical platforms which enhance the mobility ability of both autonomous and tele-operative robots. The 6-DOF manipulator makes robot capable to accomplish inspection and manipulation tasks decently. Finally the design of control systems and electronics controllers play an important role to implement the missions as desired as possible.**

***Index Terms*—RoboCup Rescue, Team Description Paper, Autonomous Rescue Robot, Tele-operative Rescue Robot, Manipulation System.**

I. Introduction

MANY earthquakes take place every year around the world. One of the most important factor in rescue operations is to find and save victims in time. Besides, a rescue scenario is usually unstructured and unstable environments, requiring the use of a combination of complex mechanical designs and control strategies both in software and hardware levels. So implementing high technologies such as robotics could be helpful for search and rescue missions.

In this paper, the MRL Advanced Mobile Robotics Lab and its robots are explained. The MRL team is planning not only to take part in Robocup competitions, but also to design and present practical robotic solutions for real life disasters such as earthquakes which are very common in our home country, Iran.

Naji I and Naji IV are two types of rescue robots which were designed with a high power and flexible mechanism, in order to overcome obstacles, are also capable of supporting a powerful manipulator for carrying objects. Figure 2 illustrates

Fig. 1. Karo, a track tele-operative rescue robot, and Adrina, an autonomous rescue robot, in Robocup Rescue 2015, China.

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NAJI-I in Robocup 2005 and Naji IV in Robocup 2008. Naji

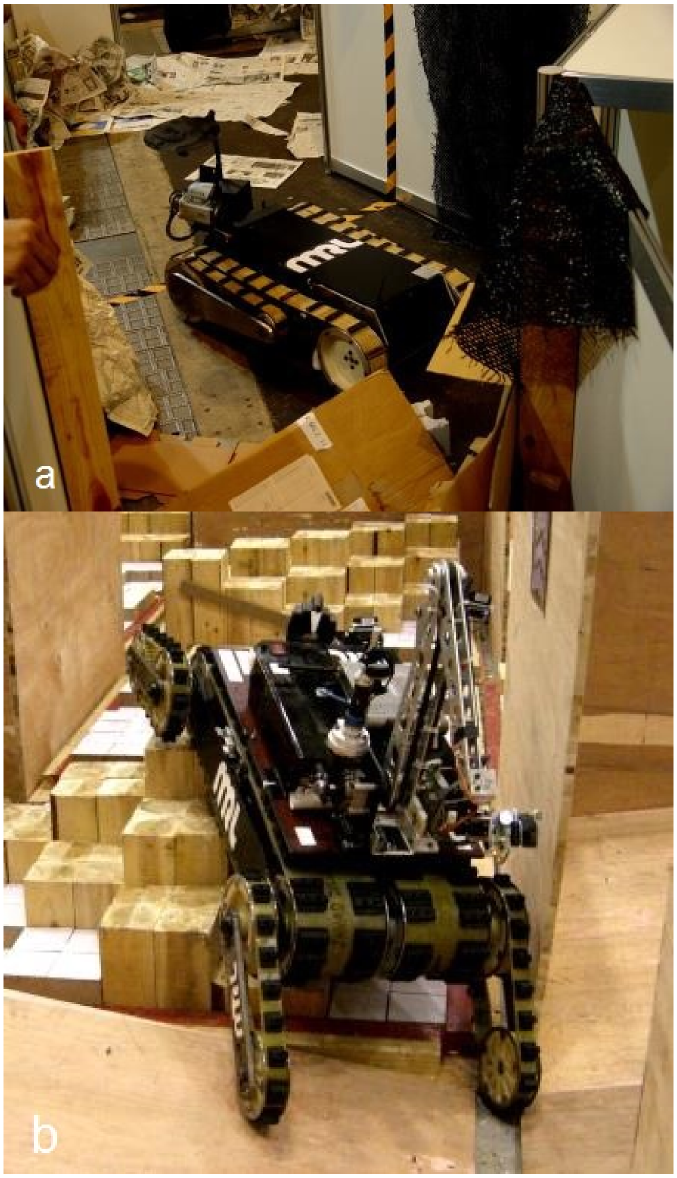

Fig. 2. a: Naji I in Robocup Rescue 2005, Japan. b: and Naji IV in Robocup Rescue 2008, China.

III is a modified version of Naji I which is more powerful and flexible while it is lighter and smaller. In 2008, a new Autonomous robot Naji V was designed for the competitions. Figure 3 illustrates the Naji V and Naji III in Robocup 2008. There are so many rough and hard terrains in a disaster situation, therefore, the rescue robot should be fast enough and low weigh to pass and explore environment quickly while remain stable. Thus a new mechanical design with 4 arms named Naji VI was developed in 2008 which is equipped to roller cylinders in its bottom. Naji VI with the new stylish is now more stable and efficient than previous ones, plus, using a new mechanical design in NAJI-VI makes this robot more effective in step-fields. In other word, Naji VI is a combination of Naji I and Naji III. By this new design, the capability of Naji I in climbing and the excellences of Naji III in step-field passing were combined. Figure 4 illustrates Naji VI in

Fig. 3. Naji V (Autonomous Robot) and Naji III in Robocup Rescue 2008, China.

Robocup 2007.

For Robocup 2010 competitions, two new robots were designed; Naji VII a tele-operative robot and Viana an autonomous robot. Viana, facilitated by most required sensors, is an autonomous mobile robot to carry out different research programs and is also suitable for the radio off zone arena. Due to improvements in autonomous field the mechanical platform of autonomous robot is improved as well. Therefore, Viana uses a four wheeled differential moving system so that it can cross easily the sloped floor arenas. Scorpion, the next generation of tele-operative robot, consists of 4 flippers attached to the main body. Each of these flippers has two links as shown in figure 5. Second part of each flipper has a self-relative rotation to the first part of the flipper with a series of gears. This causes the robot to have a capability of driving both parts of the flipper with one motor and gearbox. This property helps robot to have more flexibility in rough terrain. Another marked property of this robot is using light-weighted materials. For example, fiber carbon, titanium and aluminum are used for the main body and the other parts. Power train system contains two Maxon DC motors coupled with worm gearboxes which speed up the robot up to 0.5m/s. Team MRL achieved 1st place in Mexico 2012 Robocup competition. Ario is an unmanned ground vehicle (UGV) designed for a wide range of rescue missions. It easily climbs stairs, rolls over rubble and navigates narrow passages. Its timing pulleys equipped with an integrated suspension system isolates vehicle from road noises and vibrations. Power train system consists of two bevel gearboxes that are directly coupled to driver shafts. Ario moves by tract belt system designed and fabricated specially to deliver a high driving force to the UGV.

A new version of tele-operative robot, Karo, was designed and fabricated in 2015. The main purpose of this improved design, was to achieve reliable mechanical platform, efficient power transmission and sophisticated control system. Most of the rescue robots are required to perform tasks in real disaster sites, which demand accurate, light weight and soft-controlled manipulators. Manipulating objects and finding the victim's

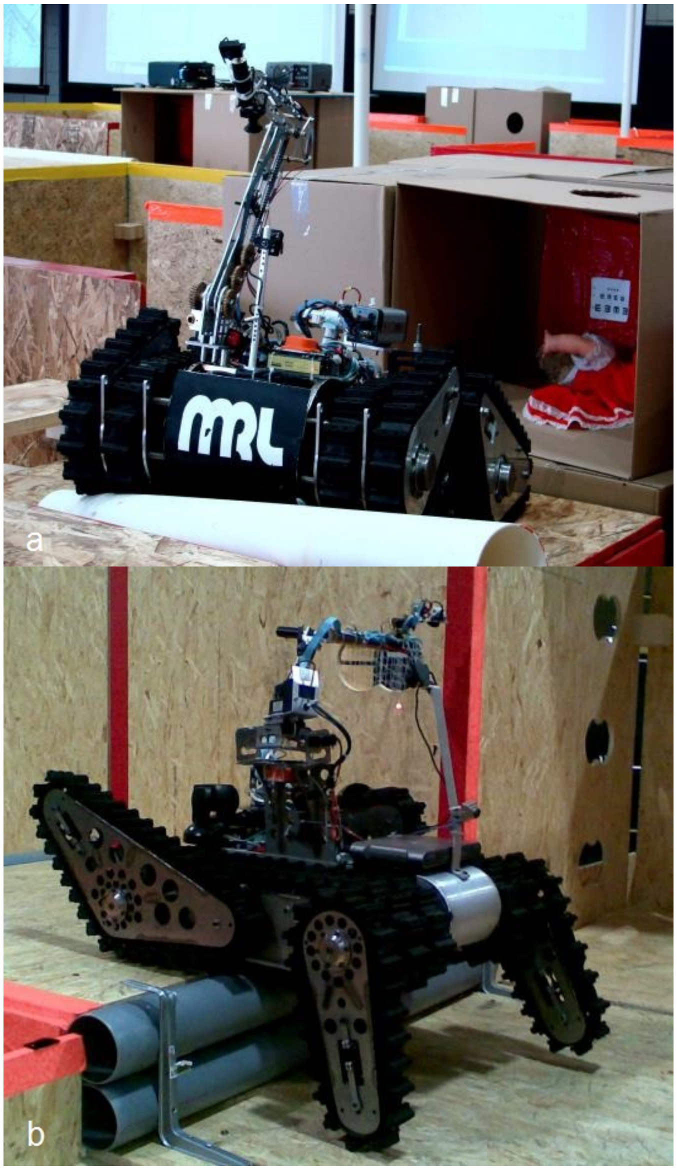

Fig. 4. a: Naji VI in Robocup Rescue 2007, US. b: Naji VI in Robocup Rescue 2009, Austria.

location are the most critical tasks in rescue missions. In addition, the manipulator should enjoy light weight and rigid structure with sufficient degrees of freedom (DOF).

Adrina is designed and implemented in order to move in rugged trains. In comparison with Viana, Adrina uses double wishbone suspension and steering for each wheel independently. Suspension system increases the robot's stability as it enters in an uneven train and prevents the robot from being overturned. Independent steering for each wheel in Adrina's design increases its maneuvering on unstructured environments.

II. System Description

Since most of the idea generation processes and development procedures have been progressed in the laboratory, some brief descriptions of hardware, software, communication and human-robot interface are provided in this section.

Fig. 5. Scorpion in Robocup Rescue 2012, Mexico.

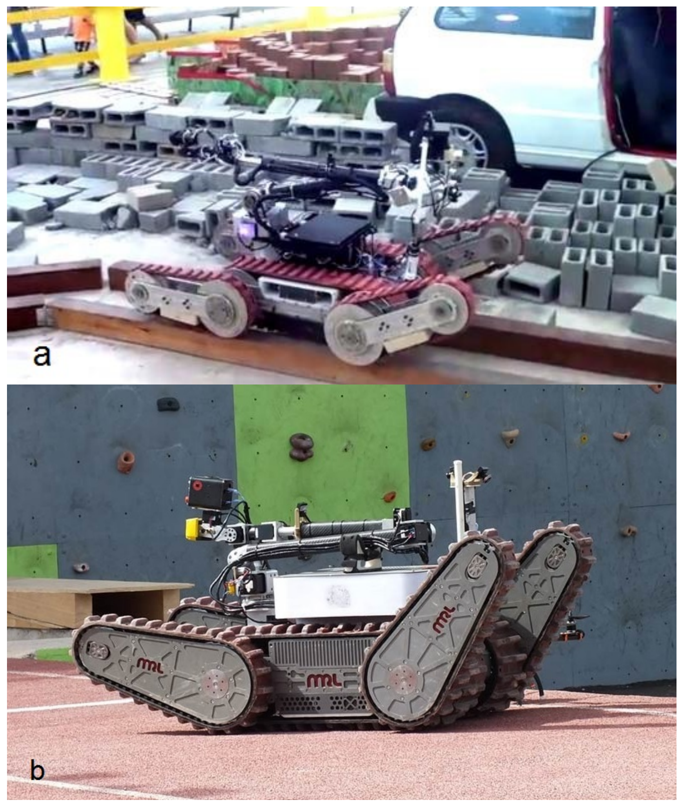

Fig. 6. a: Ario in Robocup Rescue 2014, Brazil. b: Karo in Qazvin firefighter's training camp, Iran.

A. Hardware

A brief description about hardware of Karo, tele-operative rescue robot, and Adrina, autonomous rescue robot, is explained here:

1) Electronics: Robot control system includes a main unit, which is designed based on ARM-cortex m3 microcontroller, LPC1768. This unit is equipped with ethernet, CAN and RS-485 interfaces in order to communicate with driver motors and

Fig. 7. Adrina in Robocup Rescue 2015, China.

wireless device.

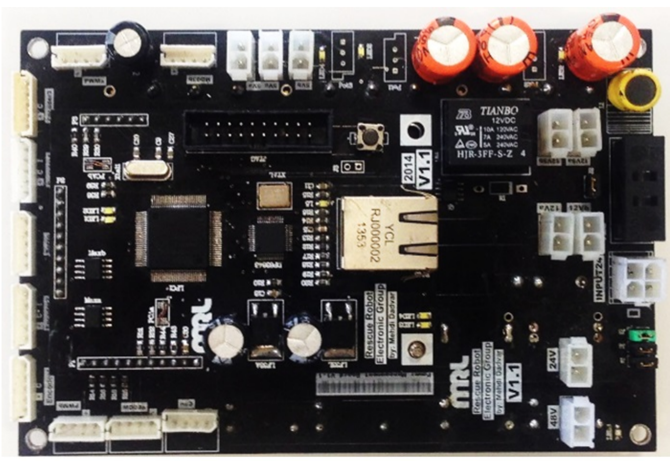

Fig. 8. ARM-based main controller.

2) Manipulation: The manipulator has 6 DOFs which is capable of reaching 140 cm. In this manipulator, three out of the six motors are placed before the first link. Power transmissions utilize timing belts, ball screws and sophisticated ball bearing arrangements. These power trains provide an accurate and precise motion for the manipulator end-effecter. Main links rotate with 15 rpm without considering destructions. End effecter of this serial manipulator is attached to a 3-DOF wrist which provides the manipulator with dexterity to search in tight places. To increase the reachable workspace of the manipulator, the wrist is mounted on a prismatic joint with 24 cm of stroke.

3) Sensors: Shaft Encoder: The robot's base platform is equipped with two Incremental Optical Rotary Shaft Encoders, which makes wheels odometry calculation, possible. According to slope gradient and mostly hash terrains, localization according to odometry measurement could not be a satisfying

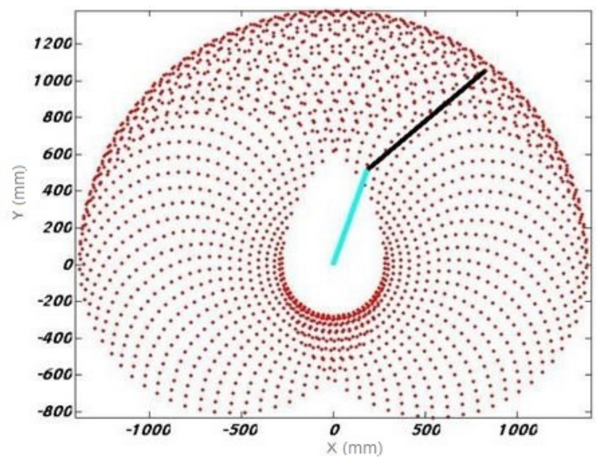

Fig. 9. Work space for end-effecter of the manipulator.

Fig. 10. Karo is inspecting insdie a car using the 6-DOF manipulator.

solution and using additional sensors measurement is unavoidable.

RGB-D Camera: Autonomous Robot is equipped with an Asus Xtion Pro Live RGB-D Camera, mounted on a Pan Tilt unit, which provides depth images in addition of RGB images. One of the major usages of this sensor is to detect and avoid impassable terrains and obstacles, by using Point Clouds acquired from camera.

Laser Scanner: 2D map of the environment will be generated using a Hokuyo UTM30-LX LIDAR mounted on a stabilizer. Accordingly, on an inclined surface, it always will be stay parallel with respect to the ground.

Inertial Measurement Unit: The changes in the attitude of the base platform, will be measured using a 6-DOF inertial sensor, Xsens MTI-100.

Infrared temperature sensor: One of the most important vital signs, for analyzing whether the victim is still alive or not, is temperature of the victim's body. Accordingly TPA 81 has mounted on the end effector of manipulator of the tele-operative robot (Karo).

CO2 sensor: In order to find out, whether the victim is breathing or not, ”MQ-9” sensor is being used on Karo and Adrina.

Thermal Camera: Detection and position estimation of victims are being accomplished by equipping autonomous robot with a Thermal Image Optris PI230, which is capable of synchronous capturing of visual and thermal images.

Analog Cameras: Four analog cameras which are mounted on the manipulator and body of the tele-operative robot, assists operator to drive the robot and detect victims.

4) Tele-Operative Robot (Karo) Locomotion: There are three major categories of locomotion systems in the field of rescue, reconnaissance or Surveillance robots; wheeled, tracked, or legged systems. Tracked systems are mostly used because of their ability to move on uneven terrains and overcome to obstacles. Tracked locomotion system is chosen for Karo robot to obtain these abilities. The two tracked layout is augmented by flipper tracks on both the front and back, independently tilted, but those tracks are driven by the main track motors.

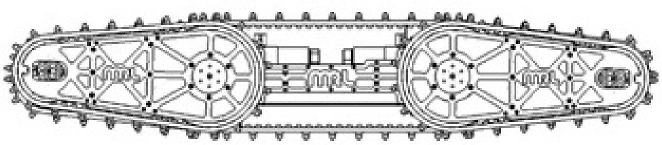

Fig. 11. Mechanical platform of karo.

5) Dynamic Analysis of Tele-Operative Robot (Karo): Using the kinetic and potential energy expressions, and applying Lagrange’s equations for a constrained or unconstrained mobile robotic system, the dynamics model can be obtained. With considering a simplified model as shown in Figure 12, the minimum torque required for climbing a surface with slope of 45 is calculated. In order to avoid a cumbersome analysis, it is reasonable to choose the input torques such that they suffice the highest torques assumed to be applicable on the system.Newton’s 2nd law can be written for the x direction:

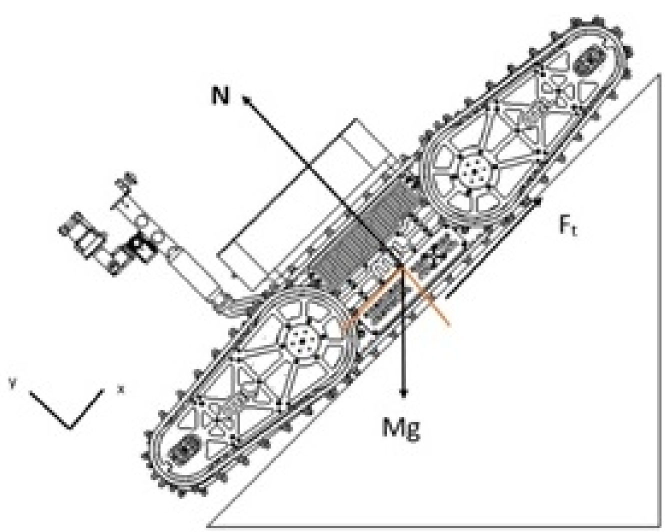

Fig. 12. Free body diagram of the robot on the slope.

$$\sum F_x = ma_x \tag{1}$$

It can be assumed that the linear acceleration and the rotational acceleration of the wheels to be zero because the final speed of robot is to be rather small and constant.

$$a_x = 0 \tag{2}$$

$$F_t = mgsin\theta \tag{3}$$

With an approximation we considered the robots mass as m=80 kg. This estimation should be made conservatively because the whole calculations should be repeated if the robot appeared to be heavier when it was completely designed:

$$F_t = 554.4\,N \tag{4}$$

Writing the moment equation with respect to the center of one of the wheels, the desired torque is determined as follows:

$$\sum M_0 = I\alpha \tag{5}$$

$$T_t = F_t r = 37.1\,N.m \tag{6}$$

6) Power Transmission of Tele-Operative Robot (Karo): The main movement of the robot is driven by two Maxon DC motors (200 W). The maximum speed is 0.75 m/s. In order to improve the abilities of running on some rough terrain, there are four swing arms fixed on the robot. They are driven by two Maxon DC motors (150 W) respectively. They can rotate 180 degrees, and can hold up the body. The tracks are made of polyurethane that has been glued on the timing belts in this system. This hand casting polyurethane is molded into particular shapes. Many grousers are equipped on the outside surface of the tracks symmetrical to reduce vibration and increase its climbing-up performance. There are many grousers on the inside surface of the tracks by which the power transmitted from the driving wheel to the tracks. They can prevent the track from leaving the wheels too.

7) Main Movement Gearbox: In order to transfer the power, the DC actuator is coupled to the spiral bevel gearbox (ratio 1:3.55) by the intermediate shaft which is the input shaft of the gearbox. to create rotary motion of the traction belt in body and flippers. The bevel gearbox’s body is the housing for bearings. Tapered bearings are used to support radial and axial loads that exerted by the bevel pinion and gear. Lock nut at the end of the pinion regulates the preload of the tapered bearings.

8) Autonomous Robot (Adrina) Locomotion: In order to provide an appropriate mobility on the field, the robot must perform a reasonable motion along the path. Once the intended velocities ($\dot{\xi}_I$) obtained from the path, a set of specific inverse kinematic equations must be used so the robot could pose a correct configuration on the path. In this case, this configuration is a set of parameters indicating angular velocity of each wheel about its axis ($\dot{\phi}$) and angular position (β)/velocity

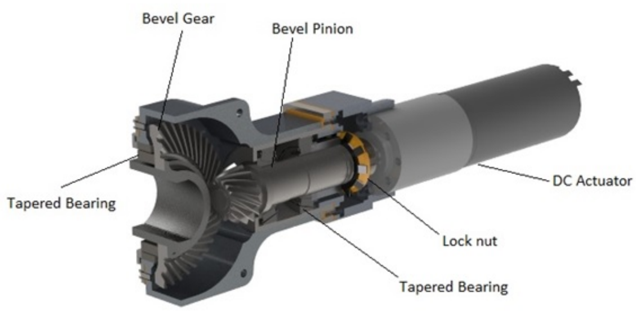

Fig. 13. Bevel gearbox assembly of Karo.

($\dot{\beta}$) of each steer joint. Following equation specifies these parameters by given velocity matrix [1].

$$\begin{bmatrix}\sin(\alpha{+}\beta) & \text{-}\cos(\alpha{+}\beta)d & l\cos(\beta)\end{bmatrix} R(\theta)\dot{\xi}_I - r\dot{\phi} + d\dot{\beta} = 0 \tag{7}$$

Moreover, it convenient to assume the sliding constraint enforces that the component of the wheel's motion orthogonal to the wheel plane must be zero. So the following equations is used to obtain the angular position of steer joints (β) [2].

$$\begin{bmatrix}\cos(\alpha{+}\beta) & \sin(\alpha{+}\beta) & l\sin(\beta)\end{bmatrix} R(\theta)\dot{\xi}_I = 0 \tag{8}$$

9) Autonomous Robot (Adrina) Suspension System: Firstly, it is notable that the role of suspension system in mobile robots is different from a vehicle. While in a vehicle the goal is to provide good ride and handling performance, maintaining the steering control and insulating high frequency vibrations [3], Adrina's suspension system aims to:

- Keeping the robot align in rough terrains.
- Maintaining contact between every wheel and ground. In other word, distributing weight equally in every wheel, which results maximum overall traction force.
- Improving advantage of the robot in obstacle climbing.
- Maintaining robots stability in uneven places.

There are several approaches in order to propose a suitable criterion for dynamic stability of wheeled mobile robots. Adrina has a double-wishbone suspension system on every wheel. The geometric parameters of suspension mechanism have been specified in order to maximize suspension working area. Also spring and damper properties have been calculated and estimated considering robots overall weight and the roughness of environment and the shape of the obstacles [4]. It is notable that stability analyze also has a huge impact on the appropriate suspension parameters.

B. Software

1) Simultaneous Localization and Mapping: In the past years the use of Occupancy Grid Maps due to the need for key functions required for mobile robots such as localization, path planning, collision avoidance, have been increased [5]. The SLAM itself has been an active topic in the past decade. Since the USAR environments are unstructured and non-planarity, normal planar indoor solutions [6] are not applicable. Another downside is that they rely heavily upon accurate odometry which is noisy and uncertain or even unavailable. These facts trigger the need for a flexible SLAM system with full motion estimation. Recent research in this field [7] have resulted in developing a robust SLAM system with 6 DOF motion estimation. Improving the accuracy of the map, a modern LIDAR system with high update rate have been mounted on the robot too. In order to give an overall consideration of the disaster site to the firefighters instead of giving them piece by piece information, a map merging framework has been developed which finds transformation between two maps and merges them accordingly. Figure 14 shows a merged 2D map acquired by an autonomous and a tele-operative robot. In addition to 2D mapping, in order to generate a 3D model of environment, an open-source framework which is based on octrees and uses probabilistic occupancy estimation has been used [8]. The generated 3D model is used for detection of impassable trains in the environment.

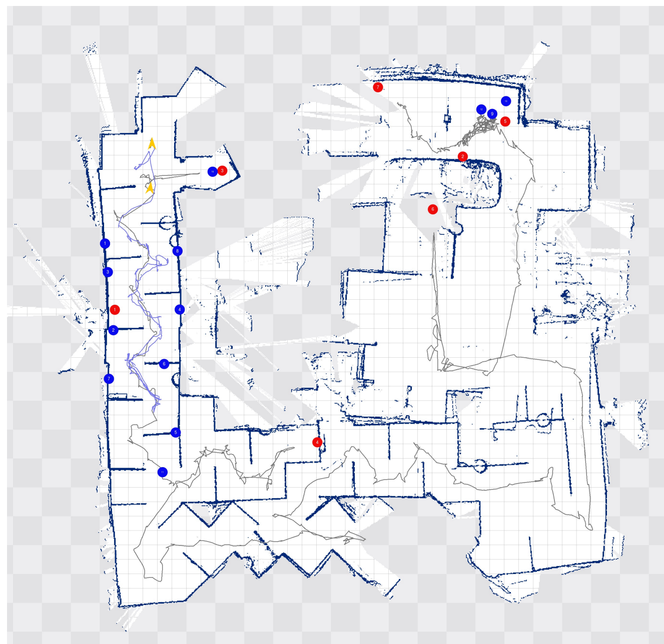

Fig. 14. Illustrates the generated merged map by MRL autonomous and tele-operative robots at the final mission of RoboCup 2015.

2) Autonomy, Path Planning and Navigation: Navigating through the unknown USAR environment is the main task of the robots in the Robocup Rescue. Moreover they must collect information regarding the environment consisting victims positions, QR codes, objects and other points of interest. In order to achieve these goals, a highly modular system has been developed. It consists of several layers such as behavior control, global path planner and trajectory generation. The high level behavior of the robot chooses between moving towards a potential victim and exploring the environment. The global planner task is to find the goal points with the aim of maximum coverage and minimum distance travelled. It tries to find the shortest tour which covers the whole environment. Due to the fact that the environment is unknown and the map is unavailable its extremely challenging to find the best tour, but as the map becomes larger, the output result becomes more reasonable. Another challenge of the global planner is that the task of finding the shortest tour is computationally expensive, accordingly the techniques for finding the shortest tour in the dynamic environments have been used and the results were promising. In contrast to other path planning methods, like wall following [9] or frontier exploration [10], the presented method significantly increases the performance of the robot. After finding the goal point and a path towards it, trajectory planner starts its job by generating trajectories that fit into the current state of the robot and the goal that it tries to reach. Since Adrina has a lot of motion constraints, the available trajectory generation methods [11] [12] don't provide a satisfying result; hence there was a need for developing a customized trajectory generator which fully accommodates with Adrina. Recovery behaviors [13] also have been developed so that when the robot is having a collision, they take over and handle the situation. Future works in this fields are multi robot support in global path planner, better detection of the topology of the environment, improving motion planning, failure recovery behaviors, etc.

C. Communication

The robots have been equipped with UBIQUITI Networks 802.11a/b/g Bullet M5 Access Point/Bridge. Choosing IEEE 802.11a 5 GHz standard has allowed achieving the maximum efficiency without having the difficulties of 802.11b and 802.11g. 500MW power ensures robust signal to overcome long distances. Controlling tele-operated Robot, video and sound streaming, system diagnostics, sensors feedback, visualizing procedures and localization and mapping in a remote station are the most common usages of this type of communication.

D. Human-Robot Interface

Human supervision and control of the robots are accomplished using two independent but closely packed software. Since they are integrated with ROS [13] as the middleware, and their cores are different (ROS does not have a built-in system to allow a single node to connect to multiple ROS cores), the task to create a integrated GUI is extremely difficult. They have to be designed in such a way that they seem like a single software. The colors for user interface are chosen based on their meaning, the controls are minimal and only provide a high level control over robots. They are also highly dynamic, thanks to rqt_gui plug-in, their features can be adopted and customized as needed. The autonomous robot can be started in fully autonomous mode and the controls provided by the interface is just used for further diagnostics and confirmation of the victims. The tele-operative robot GUI is mainly used for visualization purposes such as video streaming and sensory data but it also controls the mapping and armed or unarmed state of the robot. The commands from station only sent to the robot if the state is armed, this feature ensures that no unintentional commands is sent to the robot, just like armed mode in UAV robots. In addition to joysticks, the tele-operative robot also can be controlled using keyboard or other types of controllers, using an abstract ROS node, which can be easily modified according to the type of joystick.

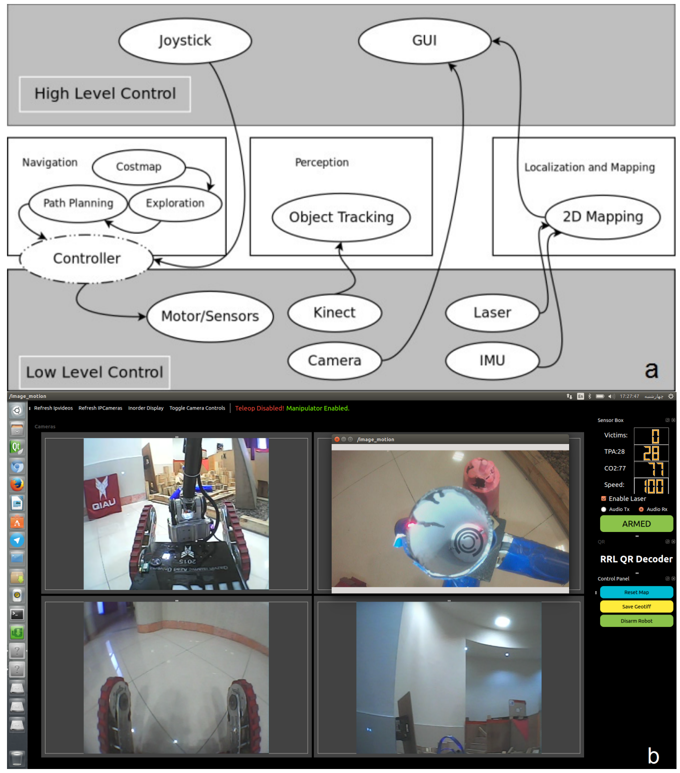

Fig. 15. a: Software system block diagram. b: GUI of human-robot interface.

III. Application

A. Set-up and Break-Down

In the rescue operation, it is desirable to set-up and break down the robot operation system in less than 10 minutes. An Operator Control Unit (OCU) including a small form factor PC, joystick, access point, antenna, monitor and waterproof case so that the operator can setup and drive in a user friendly environment.

B. Experiments

A simple test arena is provided in the laboratory to put the robots into the test. This test arena includes, stairs, inclined planes, step-fields, continuous and crossing ramps, pipe-steps, pipe-stars and victims.

C. Application in the Field

Karo accomplished a mission in a fire station's test bench. This mission evaluated the robot's performance as a surrogate. this cooperation was arranged to put the technical features of the rescue robots in some prespective.

IV. Conclusion

Several remarkable lessons, about robots' functionality, are learned from taking part in Robocup Rescue competitions and accomplishing several practicing missions; the most notable

Fig. 16. Stairs and inclined planes are provided in the test arena inside the laboratory.

one is that developing different aspects of technology on rescue robots make them capable to execute their duties more decent, from a rudimentary task to more complicated ones. However, durability, stability and robustness are some game-changer factors which prevent the performance of systems from decreasing during the time, regardless of condition's changes.

Fig. 17. Karo in a dark zone, evaluation test, Qazvin firefighter's training camp, Iran.

Fig. 18. Robot's vision system failed during reconnaissance in a smoky room.

Appendix A
Team members and Their Contributions

- Farshid Najafi — Supervisor
- Mehdi Dadvar — Team leader, control system design
- Soheil Habibian — Mechanical design
- Alireza H. M. Hosseini — Mechanical component fabrication
- Alireza Hosseini — Multi robot SLAM
- Behzad Peykari — Mechanical design
- Hamed Bagheri — Electrical design
- Hossein Haeri — Mechanical design, motion control
- Mohammad Arvan — Navigation, path planning
- Mohammad H. Salehzadeh — Embedded system programming
- Qazvin Islamic Azad University — Sponsor

Appendix B
CAD Drawings

Figure 19 illustrates the CAD drwings of Karo, tele-operative rescue robot, and Adrina, autonomous rescue robot.

Appendix C
Lists

A. Systems List

Table I lists several features of tele-operative rescue robot with manipulation system. Features of aerial vehicle is listed

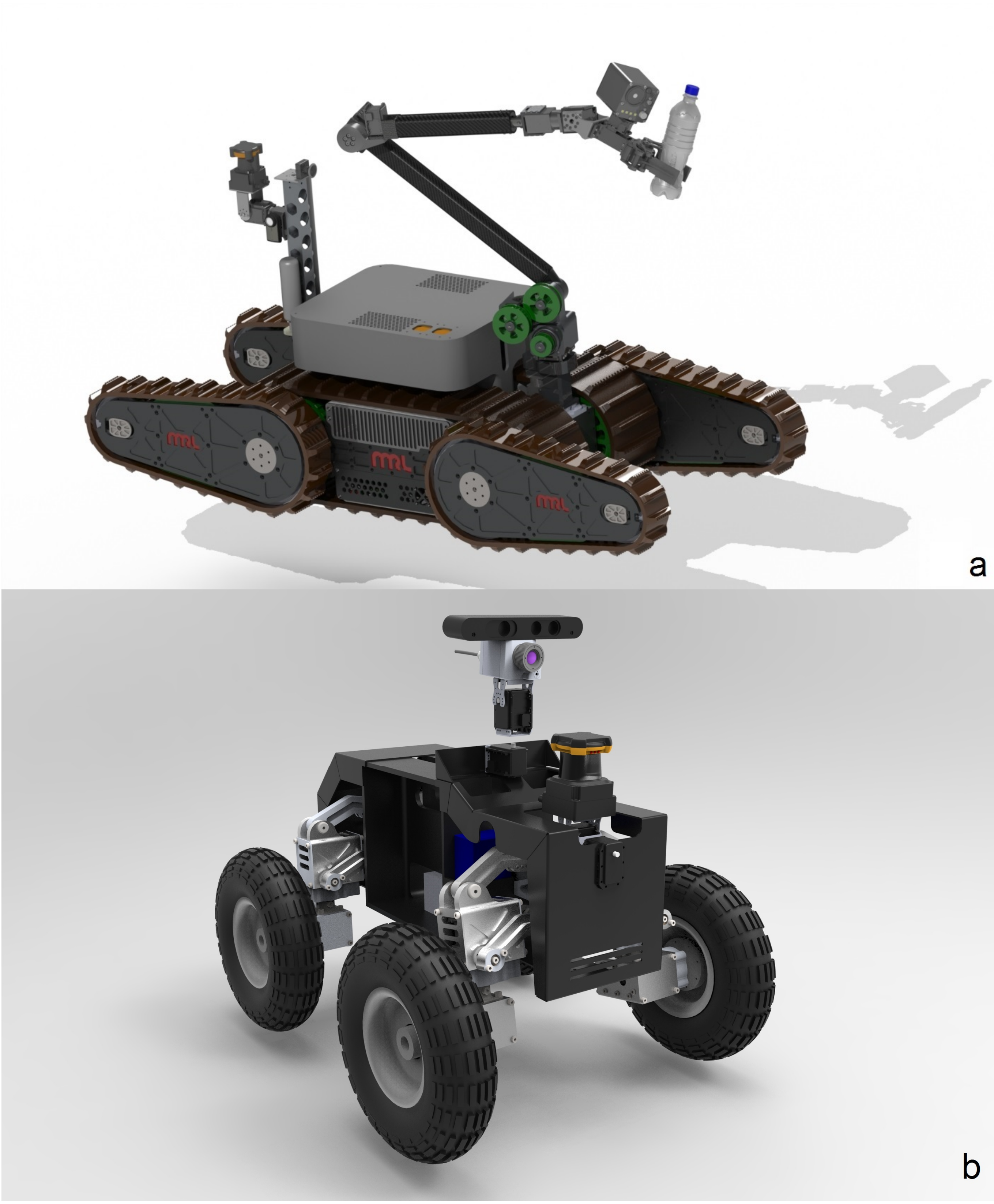

Fig. 19. a: CAD drawing of Karo and the 6-DOF manipulator. b: CAD drawing of Adrina, the autonomous rescue robot.

TABLE I
MANIPULATION SYSTEM

Attribute	Value
Name	Karo
Locomotion	tracked
System Weight	80kg
Weight including transportation case	95kg
Transportation size	0.9 x 0.8 x 0.7 m
Typical operation size	0.8 x 0.6 x 0.6 m
Unpack and assembly time	210 min
Startup time (off to full operation)	8 min
Power consumption (idle/ typical/ max)	60 / 560 / 1000 W
Battery endurance (idle/ normal/ heavy load)	90 / 40 / 20 min
Maximum speed (flat/ outdoor/ rubble pile)	0.8 / 0.6 / 0.3 m/s
Payload (typical, maximum)	1/ 3 kg
Arm: maximum operation height	140 cm
Arm: payload at full extend	1kg
Support: set of bat. chargers total weight	5kg
Support: set of bat. chargers power	300W (11-18V DC)
Support: Charge time batteries (80%/ 100%)	45 / 60 min
Cost	35000 USD

TABLE II
AERIAL VEHICLE

Attribute	Value
Name	Phantom 3 pro
Locomotion	quadcopter
System Weight	1.3kg
Weight including transportation case	3kg
Transportation size	0.5 x 0.5 x 0.4 m
Typical operation size	0.6 x 0.6 x 0.2 m
Unpack and assembly time	10 min
Startup time (off to full operation)	2 min
Power consumption (idle/ typical/ max)	20 / 120 / 250 W
Battery endurance (idle/ normal/ heavy load)	35 / 20 / 10 min
Maximum speed	16 m/s
Payload	0.15 kg
Cost	1100 USD

in table II. Table III includes information about the operator station.

B. Hardware Components List

List of notable components of Karo, Adrina and the Operator station is provided in table IV.

C. Software List

Table V includes list of all relevant software packages which is used in the robots software system.

TABLE III
OPERATOR STATION

Attribute	Value
Name	Operator Control Unit (OCU)
System Weight	5kg
Weight including transportation case	5kg
Transportation size	0.7 x 0.4 x 0.3 m
Typical operation size	0.7 x 0.4 x 0.3 m
Unpack and assembly time	1 min
Startup time (off to full operation)	5 min
Power consumption (idle/ typical/ max)	60 / 80 / 110 W
Battery endurance (idle/ normal/ heavy load)	2 / 2 / 2 h
Cost	3500 USD

TABLE IV
HARDWARE COMPONENTS LIST

Part	Brand & Model	Unit Price	Num.
Drive motors	Maxon RE 50 200 W	USD 588.50	2
Drive gears	Planetary Gearhead GP 42	USD 322.25	2
Drive encoder	Encoder HEDS 5540	USD 99.88	2
Motor drivers	custom designed	-	2
DC/DC	MKW50	USD 50	5
Batteries	Genstattu Lipo	USD 230	3
Micro controller	LPC1768	USD 8	6
Computing Unit	Intel Mini PC	USD 500	1
WiFi Adapter	UBNT Bullet M5	USD 90	1
IMU	Xsens	1200	1
Cameras	Hi-vision cctv	USD 25	4
Infrared Camera	Optris thermal camera	USD 6000	1
6-axis Robot Arm	custom designed	-	1
Aerial Vehicle	Phantom-3	USD 1100	1
Rugged Operator Laptop	Intel Mini PC	USD 500	1

TABLE V
SOFTWARE LIST

Name	Version	License	Usage
Ubuntu	14.04	open	
ROS	Indigo	BSD	
PCL [14]	1.7	BSD	
OpenCV [15], [16]	2.4.8	BSD	
Hector SLAM [7]	0.3.4	BSD	2D SLAM
Octomap	1.6.9	BCD	

REFERENCES

[1] M. Lauria, S. Shooter, and R. Siegwart, "Topological analysis of robotic nwheeled ground vehicles," in *the 4th International Conference on Field and Service Robotics*, 2003.

[2] M. Lauria, I. Nadeau, P. Lepage, Y. Morin, P. Giguere, F. Gagnon, D. Letourneau, and F. Michaud, "Design and control of a four steered wheeled mobile robot," in *IEEE Industrial Electronics, IECON 2006 - 32nd Annual Conference on*. IEEE, 2006, pp. 4020 – 4025.

[3] J. Happian-Smith, "Introduction to modern vehicle design." Elsevier, 2000.

[4] J. Wong, "Terramechanics and off-road vehicle engineering." Elsevier, 2009.

[5] S. Thrun, "Learning occupancy grids with forward models," in *Autonomous Robots*. Springer, 2003.

[6] G. Grisetti, C. Stachniss, and W. Burgard, "Improved techniques for grid mapping with rao-blackwellized particle filters," in *IEEE Transactions on Robotics*. IEEE, 2007.

[7] S. Kohlbrecher, J. Meyer, O. von Stryk, and U. Klingauf, "A flexible and scalable slam system with full 3d motion estimation," in *International Symposium on safety, Security, and Rescue Robotics*. IEEE, 2011.

[8] A. Hornung, K. M. Wurm, M. Bennewitz, C. Stachniss, and W. Burgard, "An efficient probabilistic 3d mapping framework based on octrees armin hornung," in *Autonomous Robots Journal*. Springer, 2013.

[9] P. van Turennout, G. Honderd, and L. J. van Schelven, "Wall-following control of a mobile robot," in *Robotics and Automation*. IEEE, 1992.

[10] S. Kohlbrecher, J. Meyer, T. Graber, K. Petersen, U. Klingauf, and O. von Stryk, "Hector open source modules for autonomous mapping and navigation with rescue robots." RoboCup Symposium 2013, 2013.

[11] D. Fox, W. Burgard, and S. Thrun, "The dynamic window approach to collision avoidance," in *IEEE Robotics and Automation Magazine*, vol. 4. IEEE, 1997, pp. 23–33.

[12] B. Gerkey and K. Konolige, "Planning and control in unstructured terrain," in *International Conference on Robotics and Automation*. IEEE, 2008.

[13] M. Quigley, K. Conley, B. Gerkey, J. Faust, T. B. Foote, J. Leibs, R. Wheeler, and A. Y. Ng, "Ros: An open-source robot operating system," in *International Conference on Robotics and Automation*. Open-Source Software workshop,, 2009.

[14] R. B. Rusu and S. Cousins, "3D is here: Point Cloud Library (PCL)," in *IEEE International Conference on Robotics and Automation (ICRA)*, Shanghai, China, May 9-13 2011.

[15] P. Viola and M. Jones, “Rapid object detection using a boosted cascade of simple features,” in *Computer Vision and Pattern Recognition, 2001. CVPR 2001. Proceedings of the 2001 IEEE Computer Society Conference on*, vol. 1, 2001, pp. I–511–I–518 vol.1.

[16] R. Lienhart and J. Maydt, “An extended set of haar-like features for rapid object detection,” in *Image Processing. 2002. Proceedings. 2002 International Conference on*, vol. 1, 2002, pp. I–900–I–903 vol.1.