2009 IEEE International Conference on Robotics and Automation
Kobe International Conference Center
Kobe, Japan, May 12-17, 2009

Development of Mörri, a high performance and modular outdoor robot

Antti Tikanmäki, Juha Röning
Computer Engineering Laboratory, Department
of Electrical and Information Engineering,
University of Oulu
antti.tikanmaki@ee.oulu.fi

Abstract— **This paper describes the development of Mörri, a multi purpose robot platform. The design of this robot includes mechanical, electrical and software development. Key features of the robot are modularity for multi-purpose applications, affordable size for outdoor and indoor operation, low cost, high performance, and easy to use and repair in field conditions. The main focus on software architecture development has been on creating fully-functional real-time architecture, where several algorithms and methods can be easily integrated as part of the system. As a result, this robot took part on M-Elrob outdoor robot competition in July 2008 and won "Camp Security" scenario.**

I. INTRODUCTION

Mobile robots operating in real world environment have been a subject of research for several decades. Outdoor and indoor mobile robotic platforms are an expanding area of research and commercial products. Latest developments of sensors, communication, and CPU power of computers have provided a possibility to build robots operating in real world conditions, and do real-time analysis of surrounding environments.

Many of the current robots are designed for a single purpose only, examples including lawn mowing robots [1], farming robots [2], [3], or security robots [4]. On the other hand, in research projects, platforms are used mainly for testing the development and testing algorithms and methods without focusing on any real-world applications, or even surviving in real world conditions. Through challenging competitions for field robots, like DARPA Grand Challenge (www.darpa.mil/grandchallenge/), RoboCup (www.robocup.org), and Elrob (www.elrob.eu), progress of robot's operating in real world conditions has taken giant steps forward, and made this research area close to publicity.

Instead of focusing on one application and fixed environment, our goal is to develop a "tractor" like multi-purpose platform that can be easily used in many applications and which can operate autonomously in varying conditions. To be able to perform a wide range of applications, the robot needs to be modular and easily operable. Modularity eases the reconfiguration, reuse of previously developed parts, and prevents "reinventing the wheel" on development process. In this case, modularity has been used in mechanics, electronics and software. In this paper, we describe the features and development of Mörri robot (see Figure 1). More specifically, design aspects of the robot's mechanics, sensor selection and the software features are explained. Our goal is to include all necessary aspects of autonomous, intelligent mobile robot design. The work includes high performance, but small size platform and mechanics, modular electronics, and multi purpose real-time software, where new sensors and algorithms are easy to include. With high reusability, our goal is to continuously improve robot's capabilities.

The paper consists of two main parts. The first part describes the base module and its features. The second describes a special application part designed to participate in European Land Robot Trial (ELROB), July 2008. This paper represents main features, software architecture, and operation of this robot.

Fig. 1. Mörri in M-Elrob 2009

II. PLATFORM FEATURES

A. Base

Mörri is a modular platform for multi purpose applications. It has been developed at the University of Oulu, and all the mechanics and electronics parts have been designed by the group. Platform has designed to be used in hard weather conditions in Finland, including temperature variation from -30 degrees up to 35 degrees, rain, snow and other extreme weather conditions. One major design issue has been to develop a low cost, easy to manufacture, and high performance platform, while keeping it as simple as possible to keep up easy maintenance and operate. In field robotics, fixing the robot outdoor are limited, thus the robot must be simple and easy to fix. To be able to operate in human environment, the robot must also be suitable to operate inside, and therefore

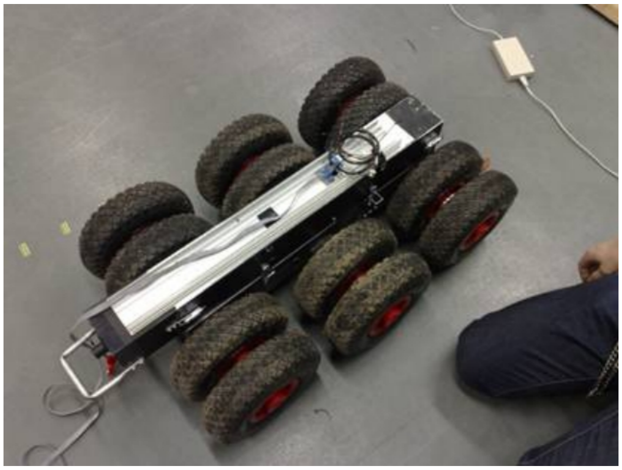

Fig. 2. Base module.

it must fit through doorways and use electric motors. With a smaller size, safety issues related to the robot harming humans and surroundings are also easier to handle.

To gain easy and fast development, most of the robot's body parts are developed from standard 100x100mm 3mm thick aluminum profile. Motors are standard Towerpro 259Kv brushless DC motors (BLDC) (costs 49 dollars / motor). A standard bike chain is used for power transmission to all wheels. Gear reduction is 1:12, created in two phases, using primary gear reduction and chain gears. All wheels are active, and the middle wheels on both sides are 16mm lower than other wheels for improving steering in high friction like asphalt. With narrow width of a bottom of the robot (100mm), it will have better grip (as having more wheels) and it moves easier on hard environment like forests.

Custom made motor drivers and controller electronics are used for driving BLDC. BLDC motors provides superior power to weight ratios as compared with brushed DC motors, and high currents can be used with small size motor. Developed driver can provide up to 3 kW to each motor. The main reason for own custom driver and controller was a lack of commercially available products, but also the power effective control of brushless motors has been a subject of research.

The lower part of the robot is a stand-alone module (see Figure 2). It contains motor drivers and controllers, 16 Ah LiPo battery, and motors and gears. All is fitted to two 100x100mm aluminum profile. This base has RS232 interface and custom made protocol is used. The motor controller is a custom made processor boards containing Atmel AVR ATmega32 processor, including two brushless servo control software and PID controls. On platform test drives, a radio modem can be connected directly to a serial port, and no additional computer is needed for remote driving.

B. *Upper part of M-Elrob robot*

The upper part of the robot (shown in Figure 1) has been designed for M-Elrob competition. Robot's sensors and actuators can be seen in Figure 3. All the sensors are connected to the main computer (Laptop) that runs robot's software. Standard of-the-shelf Laptop provides an easy-to-use, high performance, and a small size computer with own battery and display for the robot. Two 4-port USB serial converters are used to connect lasers, xSens, and radio modem. Parallel port custom made electronic serves light control, video multiplexer, and remote controller. PCMCIA Firewire card is used to capture images on board. If computing power later becomes a problem, it is easy to attach another Laptop to the robot to share the payload.

III. SENSORS

Figure 3a gives an overview of the robot's sensors and their locations. The robot is equipped with several, commercially available sensors. Four lasers (3 Hokyo URG lasers and 1 Sick LMS-291), scanning in 2D, are attached to measure the frontal area of the robot. Sick (with a practical scan range up to 40 meters) scans horizontally 180 degrees and can be turned up and down to perform full 3D scan of the frontal area. 2 URG lasers (with a range of 4 meters) are attached on vertical scan with a slightly different angle and this can be turned horizontally, providing continuous 3D scanning of the frontal area of the robot. A third URG laser is attached horizontally, scanning on the lower front part of the robot for detecting close distance low obstacles in front of the robot. The robot is equipped with a stereo camera system and one thermal camera (FLIR) and these are used by the robot's vision system. Cameras are installed on the pan-tilt head of the robot. XSens inertial measurement unit, GPS, and odometer are used to sense the location and orientation of the robot. An Extended Kalman Filter combines these for filtered position.

IV. ACTUATORS

The robot has several actuators, including the mobile base, pan-tilt head, two turning lasers and several driving lights and loudspeakers. The robot can also be equipped with a directional microphone. Direct Perception's pan-tilt unit with weather protection is used for turning the robot's head. Another same kind of PTU has been split apart for turning scanning laser (pan) and SICK laser vertically (tilt axis). The robot has several 1Watt ultra bright white led lights that provide a way to operate in conditions where no external light is available. Some of the lights are attached to the head along with head cameras.

V. COMMUNICATION

One key feature of the robot is communication. It is essential for remote operation, but also for remotely monitoring the operation of an autonomous robot. In remote operation, the range of control, low delays on control, and quality of communication are essential. In this work, direct peer to peer communication between the robot and base-station was used.

Robot uses several kinds of radios on communication. For M-Elrob 2008 competition, analog video link and radio modem was used. A free band radio, developed by Satel, operating in 869,4125 MHz, is used as a bidirectional

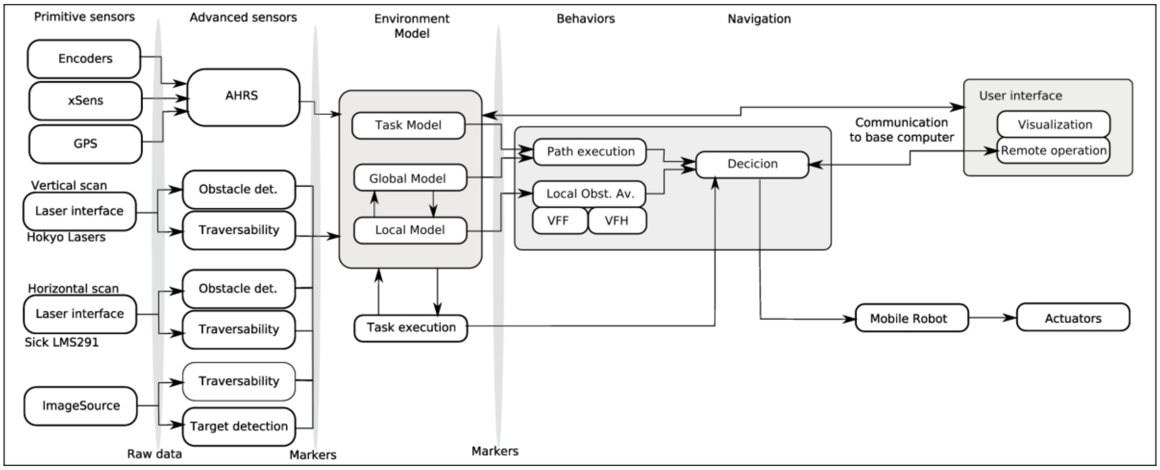

Fig. 4. Robot software architecture

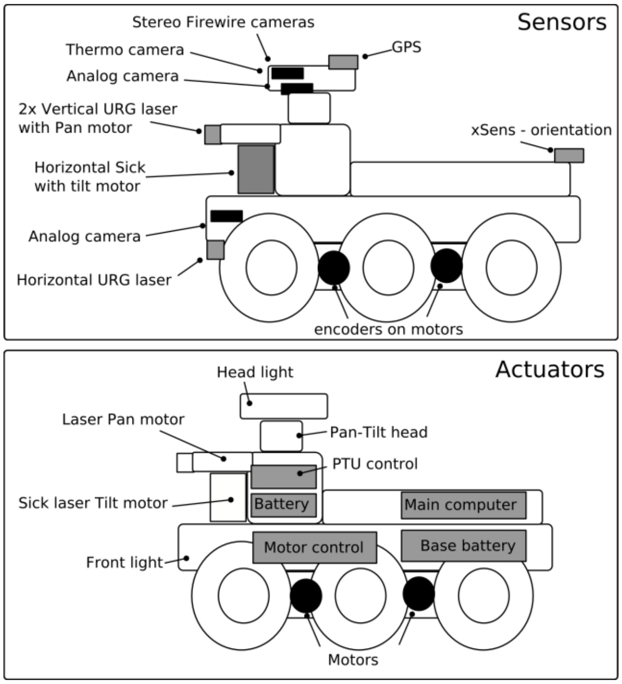

Fig. 3. Robot's sensors and actuators

serial link between base and the robot. Communication uses custom protocol, developed in Property Service architecture [5]). Link gives the maximum baudrate 19.2kbits/s, which is enough for remote operation and direct driving, but it can also be used for temporary transmitting laser scans or high resolution images from robot. As baudrate is low, this usually may take several seconds, which blocks all the other communication.

In our previous work [6], our remote operation based on WLAN communication using standard components like digital (Firewire) cameras, image compression software, UDP sockets, and decompression of images in remote operation computer. This however leads to too long delay on video (over 0.5sec) and makes direct driving hard and oscillating. The easiest solution for this delay problem is to use an analog video link. For video, we use an analog video link with a 5 Watt amplifier. It uses a custom fixed 2.38GHz frequency, as official power limits for free 2.4GHz band are too low. In real world experiments, we have achieved up to 700 meters video link with this 5W amplification. The robot has separate analog cameras for remote operation and Firewire cameras for its vision system. As mentioned earlier, images of Firewire cameras can also be transmitted to a remote operator. Analog camera signal can be switched remotely using relays.

In the robot, omni-directional antennas were used. In the base station (i.e. remote operator's location), directional antennas were used. Both antennas are turned using a motor to the current direction of the robot. The antenna also has a scan functionality, where it searches the best direction of the robot's signal strength. In the remote operation mode, a link watchdog is used. If the robot does not receive driving command in every 0.1 second, it stops. The same kind of watchdog is used in serial port communication between the main computer and robot's base.

VI. SOFTWARE

The main modules of Robot's software are presented in Figure 4. It is based on Property Service Architecture [5]. The structure of the architecture is as follow; each sensor provides raw measurements based on predefined sensor types. Types are divided into lasers, image sources, etc. Each sensor has attributes of pose (position and orientation) relative to the robot's origin and output of raw measurements in own coordinate system. On "advanced sensors" level, each estimator provides output of detection in a marker [7], [8] format. The marker is a structure representing an object around the robot or any abstract feature related to the robot's operation. Each marker consists of a position and properties representing the features attached to the marker. For example, detected objects of vision system, or clustered data points of laser scan forms a marker in the robot's local coordinate system. Abstract markers can be, for example, task-related ones such as the route points or virtual obstacles that are limiting the operation area of the robot. Each marker also has probability value, describing its certainty of existence.

A. Estimators

Estimators are modules that convert raw sensor data to marker format. An estimator may use one or several algorithms, and each algorithm can be used by several estimators. Estimators are responsible for creating unified formatted data to the local environment model of the robot. Each estimator therefore takes care of the sensor coordinate system to the robot's coordinate system conversion. Two type of estimators exists, depending on real-time requirements. All obstacle estimators must be executed within a control cycle, while "slower" estimators, like a sign detector, may take several cycles for one detection.

Marker format is used to deliver data between modules. A marker is a combination of Interest point, 3D object and list of target's features detected by each estimator. Each estimator provides output markers to a local environment model. If a global map collection is enabled, local map changes are updated to the global map according to estimation of the robot's current pose.

In Elrob version of the robot's software, following estimators were used: Robot Position Estimator, Road Traversability estimator, Thermal image estimator, and road gradient estimator.

Robot Position Estimator estimates current global position, orientation and movement of the robot, combining information from odometer, xSens orientation sensor, GPS, and it uses an Extended Kalman filter for data fusion. For representing a global position, we use the UTM coordinate system as it is a global and metric format.

Road traversability estimator uses a stereo camera and the vision system described previously on [6], using texture recognition and HSV color space for detecting roads and pathways from an image.

Parallel to this, *Thermal image estimator* is used to make difference between road and vegetation along the road. The robot is equipped with a FLIR thermo camera with a composite video output connected to a USB frame grabber. As seen from Figure 5, the temperature of the road is usually warmer than outside of the road (like vegetation) and using this grayscale image, the robot can easily detect where the road is using only size and gray level of pixel areas. This simple method works well; it also works after sunset, in complete darkness, as the ground stores temperature during day time. As different material, like buildings absorb and emit temperature differently, a thermal camera can be used for remote operation in complete darkness without any external lights. A down size of our experiments was however the automatic temperature scaling of image, which led to "blindness" when very hot spot appears on the view. As many other methods, this is not ultimate solution, but it provides new information to the robot's sensing the environment. Later, our purpose is to use Thermo camera also for finding humans or other targets of interest.

Fig. 5. View of Thermo camera

Road gradient estimator uses a vertically scanning 2D lasers, that can be turned with a motor to gain a 3D scan of frontal area of the robot. The method used is simple: if gradient between vertical scan points increase more than a threshold, an obstacle marker is created. As the vertical laser is scanning horizontally, each direction in front of the robot is received. Horizontal resolution depends on scanning speed, in practice 45 degrees sector is scanned and takes up to 1 second. As robots speed depends in obstacles on front of the robot, any appearing gradient obstacle causes slowing down and therefore a better scan.

B. Environment model and navigation

The local environment model contains nearby markers that are recently sensed by the robot's sensors and processed (detected) by estimators. Markers are updated by new information from sensors, by movements of the robot, and the probability of each marker includes a certainty of markers' existence on that place. If new information of a certain marker is not received, the probability decreases. Negative information (target is not found where it is supposed to be) is also used to update markers' probability.

When good enough information (several matches on a close distance) of the target marker is received, it is copied to "a global environment model". The global model is used to route planning or finding previously found targets.

The environment model contains also "task markers" that are related to the current task of the robot. This may include route points, i.e. a list of targets along the path, virtual obstacles (for limiting operation area), or other markers that are needed to execute the task.

For performance issues and real-time requirements, the maximum number of markers can be limited. Also, by limiting the maximum distance of a marker from the robot, the size of the model can be reduced. Each estimator must also do precessing within a control cycle.

1) Traversability: Several estimators are used to estimate traversability of surrounding environment. These estimators process camera images, thermal image, or laser scan data. The detected value of traversability is a normalized value between 0.0 and 1.0, where 0.0 is impossible while 1.0 is a clear area. Each estimator provides a set of markers representing traversability of certain area, with size and location in the robot's coordinates. These markers are used to calculate possible clear paths to a target location.

C. Route following

Autonomous driving of a given path is operating as follows: after a route (list of GPS points) is uploaded to the robot, it starts to execute it. "Carrot Point" is calculated according to the closest positions near the current location of the robot. This carrot point tries to pull the robot as close as possible to segments between route positions, while each obstacle in the local environment model pushes the robot. By combining these forces, we get several possible direction of movement, with weight. This method is called Virtual Force Field method [9]. By weighting forces created by obstacles, we can tune how close the robot can move to obstacles. For recovering from "robot traps" (also known as a local potential minimum) we create random noise forces. Local model markers are used for calculating repulsive forces, and markers location, direction and other properties (like traversability, size, type) affect on how strong repulsive force will be.

On each control cycle, the robot calculates a new temporary path to the target position (carrot point), by calling a force calculation routine recursively with steps. This improves detection and avoiding of possible traps. By calculating a new path on each cycle, it improves the handling of dynamic moving objects, or possible errors on estimating obstacles. By doing a path estimation in a local model, a short time control can be done. Similarly, the robot can do the path estimation from the global model, for example, to find routes to previously known environment.

VII. VISUALIZATION

We have developed several ways to visualize the robot's operation during tests and operation. The robot's current location, traveled path, and points of interests are visualized using Google Earth program (www.googleearth.com). Location is updated in real-time, once in a second. Google Earth's polygon drawing tool is used for drawing new routes to the robot. After a new route is saved as KML file, a Python program uploads it to the robot and the robot starts to execute it. Google earth is used also for reporting the robot's task execution. When the robot takes pictures of interesting targets, it creates an image placemark to Google Earth and user can watch images there. Communication wrapper between Google Earth and the robot's remote operation software has been coded with Python providing Property Service, and using sockets and GE API with "ctypes" python extension.

For visualizing the robot's environment model and reasoning, we have developed own 3D visualization. The visualization, shown in Figure 7, can be used to show laser scan points, output of machine vision targets in the robot's coordinate system, and path targets or reasoning vectors. The current state of the robot is updated to visualization real time, and visualization can be used for online debugging and tuning parameters, viewing what robot can sense from environment, and visualizing for example path planning and obstacle avoidance. Visualization uses OpenGL and takes the most out of state-of-the-art graphic card's advanced features.

Fig. 6. Live visualization of robot's route using Google Earth software

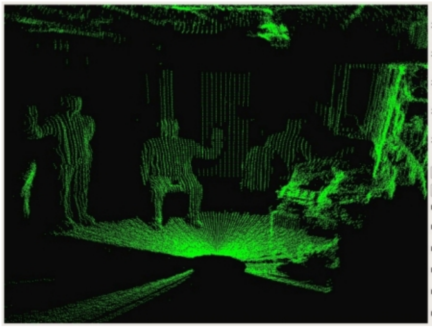

Fig. 7. Visualization of laser scans

VIII. USER INTERFACE

Figure 8 shows devices for remote-operating Mörri robot. This base station contains two laptops: one for visualizations and another for the direct driving the robot. All equipments fit in one aluminum briefcase, and can operate up to 4 hours with included batteries.

In addition to remote operation, we have developed "close operation interface", which is a wearable user interface with minimum disturbance to the user. All equipments are integrated in clothes, and a small on-hand palm joystick is used to drive the robot. This "wearable" user interface is equipped with GPS, and can be used to store a route traveled by the operation (be executed later by the robot).

IX. TESTING AND EXPERIMENTS

Through module testing, each part's operation and reliability was tested.

Strength: To test the system's power capabilities, the pulling power of the base was tested. The robot succeeds to pull up to 1700kg payload (VW Transporter van) with only about 1/4 of maximum power. [10]

Weather conditions: Several tests have been driven in bad weather conditions. Robot has been operating in rain. In snow (air temperature -10 deg), the whole system worked without freezing one hour.

Fig. 8. User interface devices

Communication link: Up to 1 km in line of sight was used on driving the robot. The major advantage of radio modem and analog video link is a very short delay that eases the operation in tight places.

Path following: Using previously explained estimators, the robot is capable of driving roads and path ways of given path. The path can be recorded by a human by walking with GPS, or it can be drawn using Google Earth path tool. Previously traveled routes are stored by the robot, and can be recovered and looped continuously by the robot. If better GPS positioning would be available (like using DGPS) human location following could also be developed.

Obstacle detection and avoidance: Using horizontal and vertical lasers, and cameras, many kind of common obstacle on path were detected and avoided. Using scanning vertical lasers, pavements, fences and vegetation were found. However, transparent (such as windows or class door) are hard to find.

One major problem of using lasers or cameras is the presence of direct sun light. If direct light hits the laser's detection chip, it freezes the whole operation and it must be manually restarted. Also a direct light disturbs the operation of cameras. We have attached a shader over the lasers and cameras.

Mörri took part in M-Elrob (European land-robot trial) 2008 on July. The robot compete on three scenario; Reconnaissance, Mule, and Camp security. In Reconnaissance, a robot must travel from 1 km distance to an area where marked vehicles should be found. In Mule, 40kg German army "rucksack" was supposed to transport as long as possible in 60 minutes. In Camp security, a robot must detect intruders on camp area and take a picture and report their location to the base station. The performance of the robot was better that expected, being able to operate in over 35 degrees hot weather. In Camp security, Mörri's size was advantage in comparison to other robots that did not fit through doorways. Mörri won this scenario, and beat up several high cost commercial platforms. In Mule, our robot pulled a backpack with weight almost the same size as the robot itself, for 40 minutes and 2.5 kilometers, becoming 4th in total points. In general, Elrob competition showed that our system was able to perform well, and generally field operation with our system is easy.

X. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

Mörri, with mechanical, electronics and software architecture provides a great tool to integrate and improve outdoor robotics research and implement real world applications. A low cost and simply structured robot can be multiplied easily and it is easy to repair it in field conditions. High performance provided several applications where robot can truly ease human work.

Through high modularity in software, developed methods are also ready to be used in different kinds of robots too. The architecture used provides all essential components of sensing, estimating obstacles and creating environment model, and reasoning operation using that information.

B. Future Works

In further works, several applications will be developed and the robot's capabilities needed to perform these applications will be improved during the process. The same robot will be participating in C-Elrob 2009 competition, held in 15.-18.6. in Oulu Finland. Several improvements will be done on autonomous operation. Before that, the base will be used in ESA's (European Space Agency) Lunar Robot Challenge, at October 2009. In LRC, a robot is equipped with tracks and a soil sampling device. In long term research, the robot's skills will be improved through applications and integrating new methods and algorithms to the system.

XI. ACKNOWLEDGMENTS

The authors gratefully acknowledge the contribution of the sponsors of the group. Team members, Ari Pitkänen, Matti Tikanmäki, Aku Pietikäinen, Sauli Särkkä, Veli-Pekka Rämäkkö, Aki Makkonen, Jussi Pitkänen, and Toni Mäkelä gave their hard work for creating the robot. This work has been partly funded by Finnish Academy and Infotech Oulu.

REFERENCES

[1] MowBot automatic lawnmower: `http://www.mowbot.co.uk/`

[2] IEEE portal for robotics and automation: `http://www.service-robots.org/applications/agriculture.htm`

[3] L. Reichenberger *Space-Age War on Weeds"* The Furrow Magazine, Summer 2007

[4] Security robots in IEEE portal for robotics and automation: `http://www.service-robots.org/applications/surveillance.htm`

[5] A.Tikanmäki, J. Röning *"Property Service Architecture for Distributed Robotic and Sensor Systems"*, in International Conference on Informatics in Control, Automation and Robotics - ICINCO 2007, 2007 9.-12.May, Angers, France

[6] A. Tikanmäki, T. Mäkelä, A. Pietikäinen, S. Särkkä, S. Seppänen, J. Röning *"Multi-Robot System for Exploration in an Outdoor Environment"*, in IASTED 2007 - Robotics and Applications and Telematics, 29.-31.Aug. 2007 Würzburg, Germany

[7] F. Brill *"Representation of Local Space in Perception, Action Systems: Behaving Appropriately in Difficult Situations"*, University of Virginia Charlottesville, VA, USA,1996, 139 pages.

[8] A. Tikanmäki *Mobile robot's environment modeling and visualization.* Department of EE., University of Oulu, Finland. Diploma thesis, 71 p. 2002

[9] J. Borenstein, and Y. Koren, "The Vector Field Histogram Fast Obstacle-Avoidance for Mobile Robots.", *IEEE Journal of Robotics and Automation*, Vol. 7, No. 3. pp. 278-288. 1991

[10] Mörri pulling VW transporter: `http://www.youtube.com/watch?v=FwYSzQM5D_Y`