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DESIGN OF THE MECHANICS AND SENSOR SYSTEM OF AN AUTONOMOUS ALL-TERRAIN ROBOT PLATFORM

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Abstract

This paper presents the design of an all-terrain wheeled robotic vehicle. The robot is tele-supervised containing several semi-autonomous and autonomous functionalities. The human operator's role is more like giving directions and targets for the robot rather that directly driving the robot. Navigating in an uncharted and non-structured environment presents a great challenge for a mobile autonomous robot in terms of obstacle detection and route navigation. The outdoor weather conditions also pose several challenges for the configuration of the robot's sensors and mechanics. The focus on this paper is on the design of the sensor system and the mechanics of the robot.

Introduction

Developing an all-terrain wheeled robotic vehicle capable of maneuvering and navigating in an non-structured environment has been an area of research in recent years. These autonomous off-road robots can be used, for example, in space research, investigating the surface of a planet without endangering human lives, or in disaster areas to locate injured persons and to give rescue personnel a more detailed picture of the area.

The development of an all-terrain wheeled robotic vehicle presents two problems of interest which are discussed here. The robotic vehicle needs to be able to maneuver in its presented environment with ease and it needs to have a way of gaining information regarding its surroundings and its status.

The goal of this project was to build an off-road robot that could participate in the Civilian European Land-Robot Trial 2007 competitions non-urban scenario and perform all the tasks required there. Environments in the competition area include urban environments and non-structured environments. Buildings and varying land profiles set challenges for the robot's communication. Other possible competitions for the robot would be Robocup Rescue, DARPA Grand Challenge or Intelligent Ground Vehicle Competition.

Work on an aerial unit that works in cooperation with the land-based unit has also been started.

Requirements for the robot

The purpose of this project was to design and build a tele-operated autonomous off-road robot. The robot was to meet the following requirements: the robot should be able to maneuver in a non-structured environment, it should be at least semi-autonomous and tele-operated, it should detect obstacles in its path, it should be able to navigate to a given location, and finally, it should be small in size and fit in the given budget of about 10,000€.

The design process started with the selection of the robot's base configuration. The robot was to be small in size and capable of maneuvering in a challenging environment, yet affordable and easy to manufacture. It was also preferable to choose an existing platform rather than designing one from scratch.

Because of the sensors and the processing unit, it was estimated that the chosen platform should be able to carry at least 3 kg of electronics. This requirement set a minimum size for the robot.

Multi-robot scenario

The robot can work together with an aerial unit in multi-robot scenarios. An overview of the multi-robot system is shown in Figure 1. The multi-robot system was presented in 2008 International Conference on Robotics and Automation [9].

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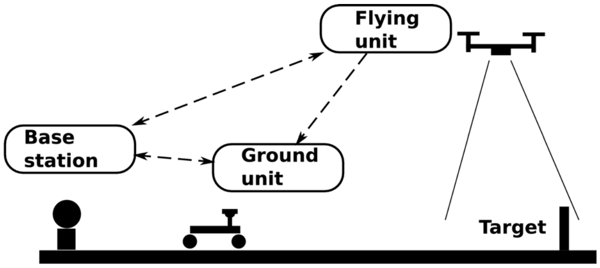

Figure 1: Multi-robot system overview

The aerial unit Ilmarinen is a semi-autonomous quad-rotor helicopter. Depending on the mission, the payload can include traditional wireless color cameras, high-resolution digital still cameras, a thermal sensing (IR) camera, as well as a multi-camera array for cockpit simulations.

The aerial unit can fly over the target area and act as a scout for the land unit. The aerial unit will locate points of interest for the ground unit to investigate and send sensor data of the area to the base station. The operator can then plan a route for the ground unit more effectively, which greatly enhances the effectiveness of the ground unit.

Mechanics design

The selection was made to go for a radio-controlled hobby car platform because none of the available robotic platforms met the requirements on price and off-road maneuverability. The platform chosen was the electric off-road hobby car E-Zilla from HPI-racing. The E-Zilla is robust and large enough to carry the extra weight of the computing system, communication equipment, batteries and the sensors. The E-Zilla is 455 mm long and 363 mm wide with a ground clearance of about 40 mm, it has two 14.4 V electric motors, four-wheel drive and a suspension system designed for off-road use with plenty of suspension travel.

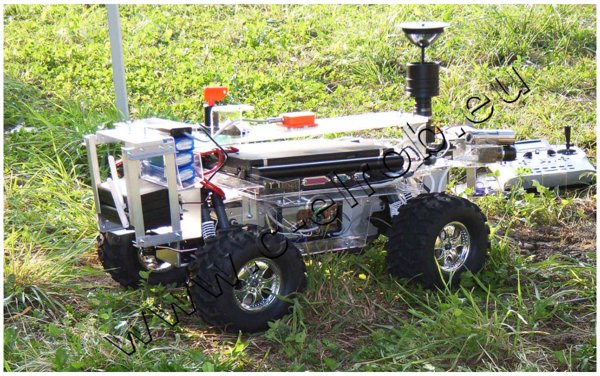

Figure 2: The robot Maahinen (image from www.c-elrob.eu)

Several modifications were made to the original RC car. Fragile plastic parts were replaced with more durable aluminum parts. The platform was modified by replacing the two original DC-motors with a brushless electric motor. The modification was required to improve the systems efficiency and allow longer operating times. A reduction gear with a reduction ratio of i=25 was installed to lower the maximum speed of the robot and give finer control of the speed of the robot. The maximum speed of the robot with the standard gear ratio was approximately 40 km/h. The reduction gear lowered the maximum speed to a much more controllable 10 km/h. In Figure 2 the robot is shown without the weather protection. In Figure 3 the sensor placement and general dimensions of the robot are shown.

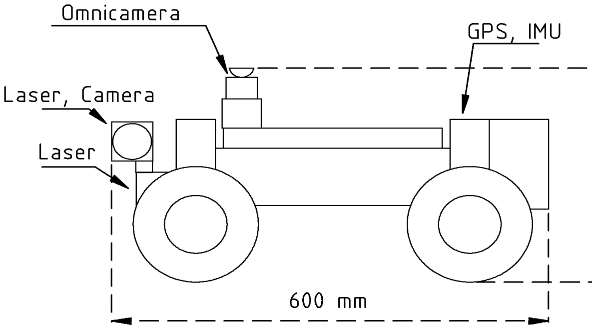

Figure 3: Sensor placing and general dimensions

The body of the car was modified to allow placing the motor and the reduction gear inside the body. This modification lowered the robot's centre of gravity and allowed us to place the electronics much closer to the centre of the robot. The body was also slightly lengthened to make room for the onboard computer system. The body of the robot was designed to protect the motor and batteries from water when driving in the rain or over shallow water. The protective shell was made from thin panels of clear plastic. The plastic panels are lightweight and extremely durable. The panels are also easy to work with. While protecting the components from water, the body also has to allow for sufficient airflow to cool the components. The cooling was aided considerably by the change from DC motors to a brushless electric motor because of the better energy efficiency of the brushless motor. The reduction gear itself has a protection ratio of IP 54, so it is already well protected against water and dust.

The tires of the E-Zilla were replaced with larger diameter tires with a deeper thread pattern to improve traction and give the robot a little bit more ground clearance. After initial off-road tests, the front and rear wheel differentials were locked to stop the wheels from slipping individually and losing power. A partially locked differential was tried but found somewhat inadequate, so a full differential lock was installed in the rear. Because of the added weight of the computer system, electronics and sensors, the suspension system of the E-Zilla had to be strengthened with stiffer springs to stop the robot from sinking too low and reducing ground clearance.

The E-Zilla had a turning radius of 1 meter. The turning radius had to be decreased to improve the robot's handling and navigating around obstacles. This was attained by modifying the rear suspension to allow the rear wheels to turn. The E-Zilla's rear suspension arrangement was similar to that of the front suspension, therefore it was possible to place a steering servo in the rear with minor modifications. The turning arms for the wheel were present in the rear; they were just locked in position. The original mechanism was designed to allow changing the wheels' toe-in. This modification reduced the turning radius of the robot significantly. On the other hand, locking the rear wheel differential increased the turning radius somewhat but the increased traction was considered more important for the robot. After the modification, the robot was able to turn with a turning radius of under 80 cm.

Sensor design

A tele-supervised autonomous robot needs to have accurate information on its position, orientation and velocity and on the location of nearby obstacles. The robot needs multiple sensors to gather all the information required and a computer to read the sensor data and make decisions based on it.

Information on the robot's environment can be acquired using laser distance sensors, ultrasonic distance sensors, infrared distance sensors or cameras utilizing machine vision. Other methods are also available, but they are not discussed here further. The most popular detection methods in robotic projects have been using a laser range finder and/or a computer vision system [3][4][5][8]. Some studies have also used infrared or ultrasound sensors as alternative obstacle detection sensors.

Two laser distance sensors and a vision system with two cameras were chosen as the robot's environmental sensors. The selected laser distance sensor was Hokuyo URG-04LX. The URG-04LX is a small-sized and lightweight 2D laser range-finder with a maximum scanning distance of 4000 mm and a scanning area of 240°. The weight of the unit is 160 g and the power consumption is 2.5 Watts so the unit is well suited for a robot with high requirements on size, weight and power consumption. The unit is not weatherproof, but it was easily protected against rain and water splashes from the ground.

One unit was mounted horizontally in the front of the robot. The second unit was mounted vertically in the front of the robot on an oscillating platform. The vertically mounted sensor provides a 3D-view of the area in front of the robot. The vertically mounted sensor can sense potholes and overhung obstacles which would otherwise remain undetected because the horizontally mounted sensor can only detect obstacles which are on its scanning plane.

Information on the position of the robot is acquired using a GPS sensor, by utilizing a machine vision system and by using odometry combined with direction information from an inertial measurement unit (IMU). Information on the robot's orientation is acquired with the IMU's 3D compass and gyroscopes. The accuracy of the positional information is greatly improved by using a Kalman filtering technique to combine the odometry, orientation and velocity information from various sensors with the positional information of the GPS sensor. The GPS sensor selected for the robot was GlobalSat BU-353. The sensor uses a SiRF Star III chip and has a sensitivity of -159 dBm. The chip supports WAAS/EGNOS corrections for greater accuracy. It is waterproof so it can be installed on the top of the robot for better reception without additional weather protection. A Xsens MTi Attitude and Heading Reference System was used to get the heading and inclination information of the robot. The Xsens sensor uses a 3D compass together with gyroscopes to provide the sensor output. The gyroscopes track fast changes in heading and the compass helps to reduce drift. The compass and gyroscope data is combined in the sensor to provide drift-free heading information.

Two Flea 2 FL2-08S2 modules from Point Grey Research Inc. were selected for the vision system. The FL2-08S2 is a small IEEE 1394 camera with 1024x768 resolution with 30 fps. One camera is mounted in the front of the robot. The second camera uses an omni-directional mirror on top of the lens to provide a view in every direction around the robot. The camera vision system is presented in a paper by Tikanmäki et al. [9].

Sensor fusion

An intelligent robot has to have sufficient knowledge concerning the state of the outside world. For this it needs many sensors to gain information regarding its environment and status. To effectively use all of its sensors, a method is needed for integrating the information from different sources into a more usable form for the operating system [1]. In sensor fusion the raw sensor data from the sensors is transformed into a more abstract numeric or symbolic representation.

The robot makes a map of its surroundings based on sensory information. This map combines data from multiple sensors into a single, usable package. For example the information concerning the location of obstacles around the robot is combined using data from the GPS sensor, laser sensors and camera sensors to form a map to include the coordinates of detected objects.

To be able to take advantage of multisensor fusion, an algorithm is needed to combine the sensory information. Multisensor fusion algorithms can be classified into estimation methods, classification methods, inference methods and artificial intelligence methods.

One of the simplest methods is the estimation method [1]. In estimation method, the data from each sensor is fused by taking a weighted average of redundant information. The fused data can then be filtered through a Kalman filter to provide an unbiased and optimal estimate of the state-vector in the sense of minimal estimated covariance. The estimation method with Kalman or Extended Kalman filtering is a simple sensor fusion algorithm and it is very light in terms of computation power required. Bayesian inference allows multisensor information to be combined using the rules of probability theory. Bayesian inference updates the probabilities of alternative hypothesis, based on observational evidence. New sensory information is used to update the a priori probability of the hypothesis.

Sensor fusion is implemented using Property Service Architecture. PSA provides a general interface and data description methods that facilitate the creation of distributed systems [6]. In this work, PSA has been used to create internal architecture, likewise the hierarchy of the Qutie robot, introduced on [7]. PSA provides system components (like data storages, higher level controls) and it can be used to remote operation of the Robot. PSA also defines the format of variables, a unified format for sensor outputs, as well as encodings for communication between distributed system resources.

Computer system and communication interface

A small PC laptop system was selected as the brain of the robot. The selected computer (Lenovo X60s) is lightweight (1.32 kg) and has the required interfaces for the sensors. A USB memory module was used as the mass storage system of the computer instead of the internal hard disk. The USB module was chosen because of its smaller power consumption and much better shock resistance. The USB module is also easier to replace should it break or in software development phase when different versions of the software of the robot have to be tested. The robot has to simply be shut down and the USB module can be replaced in few seconds with a module with a new software version.

An IEEE 802.11g wireless network interface is used for communicating with the robot's base station. The wireless network interface has a fairly limited range as standard, so measures had to be taken to improve the range of the system.

A IEEE 802.11g wireless repeater solution was selected to improve the range of the communications system. The robot continuously measures the quality of the network signal. When the signal quality drops to a certain level, the robot activates a wireless repeater node and plants it on the ground. The signal is then routed through the repeater, effectively doubling the range of the communications system. By using multiple repeaters, the range of the system is increased greatly. The size and weight of the repeater is fairly small, allowing the robot to carry up to four units.

The computer is powered by its 4-cell 14.4 V 5.2 Ah lithium-ion battery and an additional 10.8 V 2.7 Ah lithium-ion battery which replaces the CD-drive in the docking station of the computer. The batteries provide the system with approximately 5 hours of operating time. The sensor system is powered by two 7.2 V batteries via a picoPSU-80 miniature power supply. The power supply is a DC-DC power supply, which has a wide input voltage area of 6 to 26 V. The power supply provides both 5 V and 12 V voltages needed by the sensor system. The power supply is very small and lightweight and has a very high efficiency of over 95%, making it an ideal choice for a small robot.

Figure 4: Map of the autonomous scenario and detected marker positions

Electronic subsystem

To reduce the number of required interfaces on the computer, an “Atomi” -based embedded electronics system was implemented in the sensor system to communicate with the sensors and the processing unit. The Atomi system is a framework for the easy construction of embedded systems, it can be used to read and operate multiple sensors and motors while needing only a single USB-bus to interface with the computer [6]. The laser range finders and the GPS sensor were operated independently from the Atomi system because of their greater bandwidth requirements. The GPS sensor is operated with an USB interface. The laser range finders and the IMU unit have the choice of using either an RS232 serial interface or a USB interface. The USB interface was chosen to be used for both sensors. The camera system uses the IEEE 1394 interface via a IEEE 1394b CardBus PC card. In Figure 5, a block diagram of the electronic subsystem is shown.

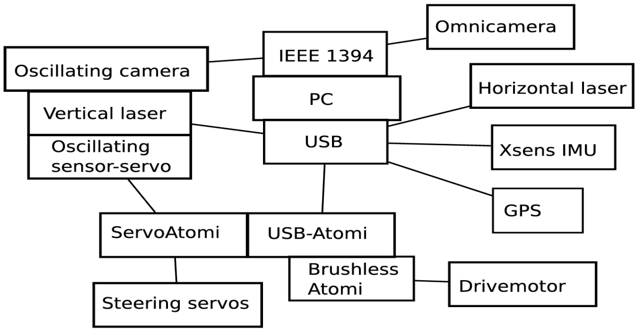

Figure 5: Block diagram of the electronic subsystem

The embedded object concept used in the Atomi system utilizes common object-oriented methods used in software engineering by applying them to software-hardware entities. The Atomi concept was used in the robot's sensor system by building an Atomi network of three units. An USB-Atomi functions as the brain of the Atomi system. It communicates with the computer and operates the other Atomi units. One Atomi unit was designed to operate the steering servos and the oscillating laser servo and another unit was installed to operate the brushless drive motor.

Testing and verifying the platform

Several tests were made to prove the concept and its reliability. The robot's intended operating environment is non-structured and previously undetermined. This presents a challenge for the testing of the robot's performance. Multiple test scenarios had to be implemented to test and verify the sensor system and the hardware and software design.

For the testing, the system was divided into units which could first be tested individually and finally as part of the complete system. Also the functionality of the whole system was tested.

The robot's low centre of gravity allows the robot to climb up hills with an inclination of up to approximately 45 degrees. The robot can drive over obstacles like small rocks up to 10 cm in height and has a turning radius of under 80 cm.

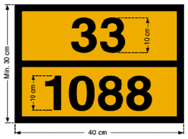

Figure 6: Example marker object

The robot was thoroughly tested in the Civilian European Land-Robot Trial's Autonomous reconnaissance scenario where it ran the 3 km urban course in 69 minutes. The objective in the scenario was to autonomously navigate a pre-designated route and to locate 5 colored markers. GPS positions and pictures of the markers had to be reported to the judges.

The robot performed well, it detected all 5 markers autonomously and recorded the GPS positions along with pictures of the markers. Unfortunately, only 1 of the GPS positions was inside the required 15 meter accuracy requirement, the rest of the positions were off by 20 – 30 meters. The autonomous functionality of the robot was not fully functional and the robot had to be manually controlled through parts of the course. Map of the Autonomous scenario and detected marker positions are shown in Figure 4.

Figure 7: Photograph of a marker from the robot's camera

Conclusion

This paper presented the mechanics and sensor system design of a small-sized and affordable, yet highly maneuverable all-terrain robot. The robot was able to participate in the Civilian European Land-Robot Trial and in the future possibly in other outdoor robot competitions with minor modifications. The project proved that an autonomous all-terrain robot can be designed and built with a relatively small budget and a small team of only six designers, most of the designers still in the thesis work phase in their studies.

The RC hobby car platform proved to be a possible platform for an all-terrain robot, while leaving most of the budget to be used on sensors and computer system.

Acknowledgments

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