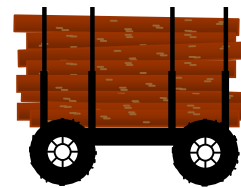


# Autonomous Navigation for Forest Machines

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*a Pre-Study*



**by Thomas Hellström**

Department of Computing Science  
Umeå University  
Umeå, Sweden

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Department of Computing Science  
Umeå University  
SE 901 87 Umeå  
Sweden  
Phone: +46 90 786 50 00  
email: [thomash@cs.umu.se](mailto:thomash@cs.umu.se)  
url: [www.cs.umu.se/~thomash/](http://www.cs.umu.se/~thomash/)

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## Executive summary

This document is a pre-study for the project Autonomous Navigation for Forest Machines. The project is part of a long-term vision, of developing an unmanned vehicle that transports timber from the area of felling to the main roads for further transportation.

The main goal of the project is to present a working solution for autonomous path tracking navigation, to be implemented in a vehicle for operation in forest terrains. The Autonomous Ground Vehicle (AGV) should operate in two modes: Path Recording, and Path Tracking. In the Path Recording mode, a human driver drives along the chosen path, recorded in the computer memory. In the Path Tracking mode, the computer assumes control over propulsion and steering. The vehicle then automatically travels along a memorized path. The operation has to account for unplanned deviations from the path, caused by imperfect sensing of position, and also by the vehicle sliding and jumping along the path. Another important part involves detection of new obstacles appearing on the path. In some cases the system should stop the vehicle and alert the human operator, who should be given the option of manually correcting the vehicle position, or giving the system the green light to go ahead along the original path.

The software and hardware will be installed in a standard forest machine, selected and prepared in collaboration with the manufacturer. A first version of the system will be installed and demonstrated on a smaller-sized robot, specifically purchased for this project. This robot will also be important for speeding up and simplifying the development.

Construction of Autonomous Ground Vehicles has been an intense research area for the last decade. A number of successful applications in agriculture and the mining industry, albeit not commercial, have been demonstrated. It is reasonable to believe that similar solutions are relevant for a forest-based AGV. However, the forest environments have enough peculiarities to make the proposed development project highly advanced, and full of challenging tasks for research.

The research work will deal with obstacle detection problems, where cameras, infra-red detectors, and other sensors are utilized to detect objects close to the vehicle. Another area of research is Path Tracking and control algorithms that take into account the specific problems involved in controlling a huge forest machine in a forest environment.

The suggested hardware solution will involve two computers connected by a high-speed radio-based network. One computer onboard the vehicle is used for low-level control and sensor interfacing, while the other, remote computer contains all the high-level parts of the system. This arrangement is believed to simplify and speed up the development work significantly.

The suggested software solution involves a behavior-based architecture, commonly used in modern robotics. The vehicle's tasks are defined as behaviors, such as *Stay on path* and *Avoid obstacles*.

Each of these behaviors is specified separately and works essentially reflexively, i.e. the action is a direct function of the current sensor input. Fuzzy logic is often used to express complex behaviors in a compact and efficient way.

Safety issues involve avoidance of human injury and damage to vehicles and environment. These problems will be given the highest priority in the project. Besides pure research, the project also involves a lot of engineering work, where existing technology is combined with innovative research results into a working product.

The preliminary project plan runs over two years. A major part of the work is assumed to be done by a PhD student financed for two years within the budget of the project.

## Introduction

This document is a pre-study for the project Autonomous Navigation for Forest Machines. The project is part of a long-term vision of developing an unmanned vehicle that transports timber from the area of felling to the main roads for further transportation. The general requirements and conditions for the development of such a product are not addressed in this document. Instead, this paper focuses on one of the necessary components: autonomous navigation, which involves sensing and moving safely according to a fixed or changing plan in the environment of the vehicle. A simplified, yet challenging, task is path-tracking navigation along a path predefined by a human operator. The proposed project aims at developing a system design, including algorithms and hardware specifications for such a vehicle.

This report is made up of six main Sections:

- Section 1 contains the objectives and specifications of the project.
- Section 2 includes a survey of a previous research, relevant to the current project.
- Section 3 contains a brief introduction to relevant parts of modern robotics, both software and hardware aspects. The presentation does not include discussions about the specific project or suggested solutions (see Section 5 for that).
- Section 4 describes the target machine and alternatives for choice of robot development.
- Section 5 presents a suggested preliminary design, both hardware and software.
- Section 6 presents a time schedule and a plan for successful execution of the project.

# 1. Project Objectives

The main goal of the project is to present a working solution for autonomous path tracking navigation, to be implemented in a vehicle for operation in forest terrains. The Autonomous Ground Vehicle (AGV) should operate in two modes: Path Recording, and Path Tracking. In the Path Recording mode, a human driver drives along the chosen path, recorded in the computer memory. In the Path Tracking mode, the computer assumes control over propulsion and steering. The vehicle then automatically travels along a memorized path. The operation has to account for unplanned deviations from the path, caused by imperfect sensing of position, and also by the vehicle sliding and jumping along the path. Due to these minor deviations, the autonomous system also has to keep constant track of obstacles such as trees and stones and avoid them by suitable corrections of the steering angle. Another important part involves detection of new obstacles appearing on the path. In some cases the system should stop the vehicle and alert the human operator who should be given the option of manually correcting the vehicle position (most likely after having removed the obstacle) or giving the system green light to go ahead along the original path. The software and hardware will be installed in a standard forest machine, selected and modified in collaboration with the manufacturer. A first version of the system will be installed and demonstrated on a smaller sized robot, specifically purchased for this project.

A second goal of the project is production of scientific papers describing the developed solutions. The papers will be printed as technical reports and submitted to international conferences in autonomous systems and related fields.

A spin-off goal of the project is to generate practical and theoretical know-how in the area of intelligent vehicles off-road. Many aspects of the development work are of universal value and the project can serve as a basis for further work within the IFOR framework.



## System Requirements

The project objectives described above determine the basic system requirement:

- The constructed vehicle should be able to record a path driven by a human operator and then autonomously travel along the memorized path.
- Obstacles in front of the vehicle have to be detected and avoided by the control algorithms.
- The developed solution should be demonstrated on a realistic forest vehicle of the same kind as proposed for the long-term goal of an autonomous forwarder of timber.

The safety aspects are of highest priority:

- The vehicle must be able to identify humans inside a safety region around the vehicle. In case of positive identification, the vehicle should immediately halt and alert the operator.
- Vehicle stability must be monitored and included in the control algorithm such that the risk for uncontrolled sliding or turnover is minimized.
- It must be possible to stop the machine by pressing emergency stop buttons that should be mounted around the rim of the vehicle.
- Bumper switches should be connected to the emergency stop such that the vehicle immediately halts if the bumpers hit an obstacle.
- Computer failure must be detected by safety electronics (watch-dog) such that the vehicle automatically stops in case of software or hardware errors.

Other requirements:

- The propulsion control should be designed such that the harm to the environment is minimized.
- The vehicle should be designed such that it, if possible, can handle difficult light and weather conditions.
- The selected sensors and other components should be suitable for the rough and hard environment in a forest machine
- The price of selected sensors and other components should be as low as possible without compromising any of the other system requirements.

## Safety issues

Safety is by many believed to be the hardest problem in developing automated unmanned vehicles [Sten01] [Reid98]. The problems to be addressed involve avoidance of human injury and damage to vehicles and environment. At Carnegie-Mellon, a system similar to the one proposed in this project is in development for pesticide spraying to citrus trees. An agricultural tractor is equipped with GPS, gyroscope, Doppler radar and four-wheel odometry for positioning and a pair of cameras for obstacle detection. The stereo camera provide both range and appearance data which are fed in to a neural network for classification. Other techniques such as infra-red (IR) are believed to be necessary for successful detection of humans and other obstacles in front of the vehicle: "The results are promising, but much more work is needed in this area".

Reid [Reid96] reports that barriers against the development of autonomous machinery already (1996) exist in some places in the US due to poor decisions on the operation of equipment in the agricultural sector: [Anonymous, 1998]: "During the last year alone, 3 people have died and 2 others suffered crushing injuries due to an "operator less" vehicle running over them"

Murphy and Morrow [MuMo96] reviews sensor types that are available or need development to improve vehicle safety by sensing human presence. Combinations of sensor technologies are suggested as solution to reliable detection of human presence.

One way of addressing the security issue in the current project is to design the vehicle to be overly cautious when uncertain situations occur. The vehicle should stop, alert a human operator, and await manual assistance. The operator can easily decide if it was a false alarm, and in such case command the vehicle to resume the autonomous operation. Furthermore, research in techniques for detection of human beings has to be emphasized during the project. Uncommon approaches such as infra-red detectors or cameras and possibly also microphones should be used in combination with "ordinary" obstacle detection sensors to improve the sensitivity and to reduce the "false negative" classifications of humans getting dangerously close to the vehicle.

## 2. Previous work

Autonomous land vehicles have been an intense area of research and development for the last decades. An excellent introduction and summary of the state-of-the-art is given in [Durr01]. In this section we report on successful projects in application areas that relate to the proposed forest based system we are aiming at.

### Forest machines

In our search for research related to our proposed development project, only one project with similar goals has been found: The ROFOR project run by Anibal Ollero, University of Seville, Spain. Not much information are to be found on the project, which has been going on since 1997. The objective of the project is the design, development and implementation of a control system for a forest processor machine (felling, cutting and to heap up). The project also includes the design of the robot arm and vehicle control system. The latest information ([http://www.esi.us.es/AICIA/2000/inge\\_e.html](http://www.esi.us.es/AICIA/2000/inge_e.html)) to be found reports:

“In this project a forest processing machine has been partially automated. Thus, autonomous and teleoperated functions have been combined in the control system. A distributed control system has been developed and implemented in the machine. The system can be implemented by using both cable and wireless communications between the operator cabin and a PLC in the processing unit. The teleoperation system integrates the joystick and other devices for machine operation, and a graphical interface for the visualisation of the processing functions during operation. The system also includes functions for machine diagnosis, operator and machine production control, and communications with a control centre using GSM. The tasks during 2000 have been mainly devoted to debugging, integration of the system, and testing.”

## Agricultural vehicles

A lot of research and development with autonomous vehicles for use in agriculture has been conducted the last decades. The primary agricultural activities addressed have been harvesting, mowing and applications of pesticides.

- O'Connor et al. at Stanford University [Ocon96] developed a system for agricultural equipment that follows a preplanned path. A four-antenna system with Differential GPS (DGPS) provided a heading accuracy of 0.1 degrees and offset accuracy of 2.5 cm.
- A row-following system for harvesting in cauliflower fields was developed by Marchant et al. [Merc97].
- At Carnegie-Mellon Robotics Institute an autonomous vehicle for cutting forage using vision-based perception on the cut and uncut regions of crop was developed [OISt96,OISt97]. The developed system used DGPS combined with wheel encoders and gyro data to compute estimates of both position and attitude. The vision sensing included functions for vehicle guidance (row-following), “end-of-row” detection, correction of illumination due to shadows and obstacle detection. An adaptive Fisher discriminant classifier was used to segment the images in cut/uncut regions by pixel wise classification based on RGB values. The obstacle detection was implemented with similar techniques where each pixel was classified as “normal” or “abnormal” relative to a training image. The probabilities for a pixel belonging to the probability distributions constructed from the training image were used to decide if the pixel belongs to an obstacle or not. Regions with a large number of such pixels were identified as obstacles. Three onboard computers were used, one for image analysis, one for control and one for task management. A pure pursuit algorithm is used for the path tracking task.

The accuracy of the GPS position estimate was constantly monitored. If it fell below a certain threshold (typically 20cm), the vehicle was halted and resumed operation when the readings were good again. The length of this break varied between 30 and 120 seconds but did on the other hand not happen very often [Pila99].

- In [NoRe98] computer vision is combined with fuzzy logic, genetic algorithms and neural networks in a system for “smart spraying” for weed control and detecting crop growth.

- In [ZhReNo99] a project involving fusion of computer vision, Kinematic GPS and a fiber optic gyroscope (FOG) is used to guide an agricultural vehicle following crop rows. The reason to use Sensor fusion is to combine the good sides of the different sensor types while avoiding the bad sides. GPS is said to be affected by reflections from trees and obstructions, computer vision is affected by soil color and changing light levels while the FOG is subject to drifting errors. By combining the three sensor types, a better performing system was achieved.
- The development project for an Autonomous Christmas Tree Weeder has been initiated with a feasibility report [Have02]. The aim is to develop a light Christmas tree weeder, that is “superior to the present heavy ineffective, costly and environmental detrimental equipment, and can make mechanical weed control competitive to chemical control”.

In a status report on autonomous guidance of agricultural vehicles, Reid [Reid98] concludes: “While all of these ideas might appear very strange to the average farmer, there are few scientific or technological barriers. Economics and ingenuity will determine which occur first”.

## Mass excavation

Automatic digging is an active field of research. One approach is to let a human operator select the digging point and to let the autonomous system take over to complete the dig. Another, more difficult, approach is to use active sensing and automatically select the dig point. Stentz et al. [Sten01] developed a fully autonomous 25-ton hydraulic excavator for loading a truck with soft material such as dirt. The machine uses laser rangefinders to recognize the truck, detect obstacles and controlling the digging and loading process. The scanners scan vertically and are mounted on a pan table swept left and right, thereby covering all space of interest. According to the authors, the excavator is a fully operational prototype but is “unlikely to appear commercially as such, at least not initially”. It does not work under all weather conditions. The system is able to detect most obstacles, but “could not be left alone to work a complete shift without incident”. One suggested way to use it commercially is to demand a human operator to remain on the machine to monitor for safety, but to let the computer take over the actual digging/loading. Alternatively, a remote operator could monitor the work, check plans for repositioning and manually make corrections when necessary.

## Mining machines

Mining is an important application domain for autonomous off-road vehicles. Stentz et al. [StOl99] report on a development of two mining aids: a system to measure and control forward motion of a continuous miner, and a system to measure and control the machine's heading. Both measures are important to ensure high cutting quality of the coal. The heading task is solved by Kalman fusion of a fiber-optic gyro with a laser/camera system. The motion is computed by correlating stereo images of the roof of the mine, taken with a short delay.

A recent project, reported in [ACFR01], use a scanning laser to detect guideposts located on the side of the haul road. The system aims at determining safe manual driving control of large haulage vehicles.

## Cross-country vehicles

In [LaRo94] the development of an autonomous off-road vehicle is presented. The vehicle manages to travel autonomously for one kilometer through unmapped cross-country terrain. The perception is performed by a 2-dimensional laser range finder that acquires 64x256 range images at 2Hz. Position is obtained by combining readings from INS and odometry (see Section 3 for more information). The ranges from the laser range finder are used to update a map of the ground, with cells corresponding to 20x20 cm squares. The squares are classified as traversable or non-traversable depending on the distribution of height information within each cell.

Singh and Digney [SiDi99] report on a the construction of an autonomous cross country vehicle involving navigation and obstacle avoidance using stereo vision combined with laser ranging. Also, functions for on-line global planning are included, such that the vehicle can backtrack and chose locally sub optimal routes to achieve a long term benefit.

In [ZhLi98], a vision system with a single binocular camera is used for stereovision. In this way optical and electrical identities of an image pair is guaranteed and the correspondence problem is greatly simplified. The technique is demonstrated with real-time obstacle avoidance.

## Space robotics

Autonomous vehicles are, for understandable reasons, very attractive for space expeditions, especially for the unmanned ones. A lot of research reports in the area are available.

A majority of the reported work employs laser rangefinders [ChAl93, HeKr93] or proximity sensors instead of stereovision. Positioning is solved with dead reckoning devices such as odometry (wheel encoders) or inertial navigation systems.

In [SiHe96], two complementary techniques are used for obstacle detection. Stereovision provides reliable indications of obstacles but operates fairly slowly. A laser-based system looks for hazards immediately in front of the rover and commands emergency stop if any are detected.

## Other related research

The Nomad robot was built to autonomously search for meteorites in Antarctica. It uses a 3-CCD color camera for detection of possible meteorites and for obstacle detection. Possible meteorites are placed in a target database where an A\* algorithm is used to plan a path for collection of the found objects. The final decision whether to collect the object or not is done by spectrometry analysis. The software includes a new control architecture, SAS, that integrates sensing, navigation, classification and mission planning.

[HoSe01] presents a rule-based Fuzzy Traversability Index that quantifies the ease-of-traversal of a terrain by a mobile robot based on real-time image data of terrain characteristics. Examples of characteristics are slope, roughness, hardness, and discontinuity. The idea is extended by adding human supervision in the training of the fuzzy rule base in [HoTu01]. The method can be used to enable off-road vehicles to make autonomous navigation decisions that guide them through the most traversable regions of the terrain.

## Current Research Areas

Technical advances in autonomous off-road vehicles are needed in three key areas [Sten01]:

- Sensor and image processing.  
This area is crucial for intelligent vehicles. Just as the approach with AGVs in general, one should realize that no single sensor is good for all purposes. Therefore we need to engineer sensors for particular applications and combine them in multi-sensor systems.
- Machines that can be trained in the field.  
The vehicles will not be fully autonomous when they leave the factory. Instead, it must be possible for the customer to train them in the field to meet the specific requirements
- Human-machine interfaces.  
The vehicles wont will need supervision and help with difficult tasks. Powerful interfaces between humans and computers are therefore needed to share control in a “symbiotic and productive way”.

Another area that is often mentioned as very important and overseen in current research is the safety aspect with dangers for humans being injured by the autonomous vehicle [Sten01, Reid98].



## Conclusions

Exemplified above, navigation for AGVs has been an intense research area for the last decades. A number of applications for outdoor terrain have been demonstrated. It is reasonable to believe that similar solutions are relevant for a forest-based AGV. However, the forest environments have enough peculiarities to make the proposed development project highly advanced, and full of difficult tasks for research.

The state-of-the-art in Autonomous Ground Vehicles provides the necessary technology to develop working systems in many application areas. The following quote by Durrant-Whyte [Durr01] summarizes the situation: "...the necessary sensors, algorithms and methods to develop and demonstrate an operationally viable all-terrain ALV (Autonomous Land Vehicle) already exist and could be readily deployed...the successful development of an operational ALV system will rely on an effective approach to systems engineering."

However, the fact that no commercially available industrial product exists to our knowledge indicates that the way to a fully operational AGV for commercial forest applications is both long and challenging.

## Domain specific problems

A lot of experience from similar work, in for example automation of agricultural machines, can be used as inspiration for the development of an autonomous forest machine. However, the forest environment introduces a range of problems and situations that have not been considered in previous research in other disciplines. This includes but are not limited to:

- Difficult ground conditions (trees, stumps, ditches, sinkage, skidding, slippage etc.)
- Special types of steering mechanisms (articulated joint steering) might call for special kinds of control algorithms
- Environmental concern
- Difficult light and weather conditions affect many sensors, in particular vision systems
- The obstacle detection system has to distinguish between "ordinary" obstacles such as bushes and small trees and "real" obstacles such as larger trees, stumps, stones and not least human beings.

These aspects have to be in focus in all parts of the project since it will affect the system from the user interface level down to the low level control of propulsion and steering.

### 3. Robotics

This Section contains a brief overview of parts of modern robotics that are considered important for the project. This includes descriptions of various sensors, general architectural issues and finally a number of well-studied sub tasks such as localization and obstacle detection. However, the problems and possible solutions specific to the current project are given in Section 5 and not in this Section.

#### Sensor Technology

Perception is a key part of an autonomous system. The most common and relevant techniques for the project are described below.

##### Machine Vision

utilizes cameras mounted on the vehicle to provide information about the environment. Many reported applications perform classification tasks with the image data. See e.g. [GeFe97]. In harvesting machines, it is important to distinguish between crop and soil areas in the images. Camera data is used to detect uncut regions of crop in [OlSt96,OlSt97] by color segmentation and classification based on histograms representing the conditional probabilities for cut and uncut pixels. The main usage for cameras in the present project would be obstacle detection and possibly map-based localization [Durr96]. Examples of image analysis for identification of trees for forest inventory can be found in [BySi98]. Stereo cameras make it possible to compute distances to objects. However, stereovision requires carefully calibrated cameras. This is generally a very tough procedure requiring lots of time and effort. Stereo perception is often used to build three-dimensional maps of the environment for proposed lunar rovers, e.g. in [KrHe95].

Batavia and Singh [BaSi01] describe an obstacle detection methodology that combines two complimentary methods: adaptive color segmentation, and stereo-based color homography. Homography is described as “poor man’s stereo”. Although computationally cheap, it does not provide true depth information. However, in combination the two methods are claimed to work well, particularly for environments in which the terrain is relatively flat and of roughly the same color.

Machine vision can also be used for localization of the vehicle. A technique inspired by the *view-based* approach is described in [MaSa02]. Image data is saved in a database during path recording, and new images are matched against the database during the actual path tracking. In this way the position and attitude of the vehicle can be estimated.

## **GPS (global positioning system)**

delivers an estimate of the robot's position by measuring the differences between time-of-flight for signals from 3 to 12 geostationary satellites. Velocity and heading estimates are also possible to compute, based on Doppler effect of signals from the satellites. The velocity measurement accuracy is about 0.1 m/s. Basic GPS receivers have a position accuracy of around 15 meters 95% of the time. (100 meters if Selective Availability is on). An extended technology is DGPS (differential GPS) which has an accuracy of around 0.5 meters [Durr01]. Carrier Phase GPS, Dual frequency GPS and Kinematic DGPS are capable of delivering a position with errors between 2-20 cm and an attitude with an error of less than 0.1 degrees [Ocon96, Reid98]. Regardless of the type of GPS, the technology has limitations that make a GPS system insufficient as the single position sensor for an autonomous moving robot. A GPS system is therefore often combined with INS or odometry. The most common problems involve [Durr01] obstruction of line-of-sight to satellites, multipath problems and active jamming from other RF sources.

## **Inertial navigation system (INS)**

measures derivatives of the robot's position by gyros and accelerometers. Most equipment contains 3-axis pitch/roll/yaw gyros and 3-axis pitch/roll/yaw accelerometers. In this way attitude and position can be calculated. INS systems are prone to internal drift problems and must be periodically recalibrated to give full accuracy. INS systems are often used as a supplement to other position sensors such as GPS.

## **Wheel encoders (shaft encoders)**

sense the rotation of the steering shaft and wheel axles and convert these to change in orientation and position. Wheel encoders are often used for odometry as a backup or supplement to other navigational sensors such as GPS and INS. Examples of combining GPS with odometry can be found in [GaRi01]. A vehicle for automated harvesting is combining GPS, INS and odometry in [PiHa99]. The normal way to perform this sensor fusion is by Kalman filtering. This is a stochastic method known to compute the optimal linear predictor from two or many signals. In [HaHe01] a deterministic approach is combined with Kalman filtering for sensor fusion of odometry and inertial sensors. This approach is reported to improve the position estimates significantly compared with a pure Kalman filter approach.

## **Compasses**

measure the orientation of the earth's magnetic field (most often only the horizontal component) relative to the vehicle and hence be used to estimate the attitude of the vehicle. Typical techniques are: gyrocompasses that uses gyroscopes pointing towards the magnetic north pole and flux-gate compasses that uses a toroidal magnet suspended in the Earth's magnetic field. This kind of sensors is very susceptible to local variations in the ambient magnetic field. Calibration is therefore essential. Also, compasses are known to be of limited value close to large metal objects and machine equipment. An alternative is to use a gyro, which provides a relative measure of the altitude of the vehicle.

## **Ultrasonic sensors/sonars**

determine distance to objects by transmitting a short pulse of ultrasound from the sensor. A receiver detects the reflection off objects ahead of the sensor, and the distance can be computed by measuring the time that elapsed between emission and reception. The sensitivity of a sonar sensor is cone shaped (typically 15-30 degrees cone) which means that the exact position of the object is unknown. However, the technique is very useful to detect free space, and is commonly used for obstacle detection in in-doors robotics. Another problem with sonars are so-called specular reflections. Specular reflections occur when a sonar beam hits a smooth surface at a shallow angle, and is therefore not reflected back to the robot, but outwards. Only when an object further away reflects the beam is a reading obtained, indicating a bigger free space than actually exists [Nehm00]. A typical maximum range with full accuracy for this kind of sensor is 5 meters (product information ActivMedia).

## **Infra-red reflex sensors**

are most typically used for distance measurements by transmitting a modulated infra-red light pulse and measuring the intensity of the reflection from obstacles nearby. In practice, infra-red sensors can only be used for detection of objects, not for range measurements [Nehm00].

## **Infra-red detectors**

measure the infra-red emission from a human body. This kind of detector is often used in intruder alarms and could be used as an indication of human presence near the vehicle.

## **Laser range finders**

also known as Ladar or Laser scanners, work by the same principles as ultrasonic sensors with the important difference of using near infrared light instead of ultrasound. Instead of measuring the elapsed time between emission and reception, the phase shift of a amplitude-modulated laser signal can be measured and used to compute the distance. The resolution and range is greatly improved compared to ultrasonic sensors and the problem with specular reflections is also much less pronounced. Typical accuracy is  $\pm 50\text{mm}$  for single 180 degrees scan operations with a resolution of 0.5 degrees. Total range is between 50 and 150 meters (product information for the SICK laser scanner). A major limitation with this kind of sensors is the high price. This has restricted their development and effective use in ALV (autonomous land vehicles) systems [Durr01]. Another problem is the sensitivity to dust, rain and snow.

## **Millimetre wave radar**

promise performance that is not degraded by environmental conditions such as dust, rain and snow [Sing97, SuKu95, ACFR01]. It is often considered to be a better alternative than Laser range scanners for the out-door automation. In [Clar99], Clark presents an analysis of how radar signals interact with common objects in typical field robotics locations. This leads to the development of natural feature extraction techniques, enabling suitable navigation markers to be identified from the radar measurements. It is also described how the identified features may be compiled into a map of the operating area.

## **Inclinometers**

are used to measure the orientation of the gravity vector relative to the vehicle. In its simplest form they can be implemented as mercury switches. More sophisticated types measures the tilt and skew of the vehicle in degrees. Typical accuracy is less than 0.5 degrees. This sensor type is highly essential since it can avoid serious disasters that would otherwise be unpredictable for the autonomous vehicle.

## **Tactile/bump sensors**

are used to create a “sense of touch” and are often used as collision avoidance sensors of last resort. They can either be treated as normal sensors or they can be wired directly into the low level control of the vehicle propulsion in such a way that they cause the vehicle to immediately halt.

## Robotics software architectures

Two major paradigms for construction of intelligent robots and autonomous systems exist: Hierarchical architectures and Reactive architectures [Murp00].

### Hierarchical systems

A *Hierarchical system* implements the tasks in a sequential and procedural way, much in the same way as one traditionally writes computer programs. The major procedures are often described as *Sense*, *Plan*, *Act*. The *Sense* part processes the sensor data and generate high-level descriptions of sensed objects. The *Plan* part normally involves serious modeling of the world and the interaction between robot and world. The actual planning is then performed in this model and the computed plan is finally executed in the *Act* part. Many drawbacks with this approach have been noted. One such is the fact that the world has often changed by the time the modeling and planning phases are completed. Another, more serious, is that the world simply cannot be modeled accurately since it involves too much noise and indeterminism.

The drawbacks with the Hierarchical approach are addressed in the competing paradigm *Reactive systems*.

### Reactive systems

In a Reactive system, the overall task is broken down into goals that should be achieved. Each task is implemented as a reflexive behavior, where the robot generates an action as a direct function of the current sensor data. Maps of the environment are not allowed and state variables are avoided as much as possible. The function of the complete system is more described by these behaviors than by a data flow as in a *Hierarchical system*.

The approach has successfully been implemented in a number of AGVs and other robots. The reactive approach has serious drawbacks as well, one of which is the total lack of memory or internal representations of the environment.

### Hybrid systems

Most real applications use a mix of the two paradigms. These so-called Hybrid systems can be described by the design principle Reacts when it can, Plans when it must. The suggested robot architecture in the current project is essentially reactive, with behaviors responsible for the obstacle avoidance and path tracking. However, the overall control mechanisms and the routines for path recording are suitable for a hierarchical design.

## **Coordination**

A behavior-based system has to include a coordination unit that combines and synchronizes the actions suggested by the different behaviors. Overviews can for example be found in [Arki99] and [Murp00]. A number of standard methods exist:

### **The Subsumption Architecture**

is priority-based and lets the behavior with highest priority control the vehicle [Broo86]. This scheme is very fast but doesn't allow multiple behaviors to produce a combined action.

### **DAMN**

is an architecture where each behavior votes for or against a set of actions [Rose97].

### **Motor schemas**

is a technique that performs command fusion by adding vectors representing the actions suggested by the different behaviors [Arki89].

### **Fuzzy logic**

has also been used to perform command fusion from multiple behaviors [YePf95, Sera00, SoSh95]. In [HaCa99], fuzzy logic is used in an autonomous agricultural vehicle for crop following. Fuzzy logic can also be used to express the actual behaviors in an autonomous vehicle. An excellent introduction to the entire topic of fuzzy logic for autonomous vehicle navigation is given in [DrSa01].

### **Utility fusion**

is an approach [Rose98] where each robot state is assigned a usefulness or utility measure. The utilities are combined with measures of uncertainty to evaluate actions based on kinematics and dynamics of the vehicle.

## Obstacle detection

The main task for the perception is obstacle detection, which is essential for a safe autonomous vehicle. Detecting obstacles implies an active perception of the environment. Typical sensors for this kind of task include cameras, millimetre wave radar, and laser rangefinders [SiHe96]. Laser rangefinders have the great advantage of providing accurate depth information that has to be computed from calibrated stereo images if using cameras for the same task. Radar has the advantage of working better in rain, mist and snow, and also sees beyond light vegetation such as bushes.

One example of obstacle detection and avoidance with low-resolution vision modules combined with reactive control can be found in [Lian97]. In [PiHa99, Olli97] images are used to identify crop lines for automated harvester. Individual pixels are classified as either cut or uncut and lines in the images are computed by regression based on these classified points. Similar techniques are used in [BySi98] to identify trees in images, such that the diameter of the trees can be determined.

Ultra-sonic sensors are also common sensors for obstacle detection. While the spatial resolution is rather low (a wide sensitivity cone) they are useful for determining the existence/non existence of obstacles in front of the vehicle.

Infra-red detectors can be used to detect human presence by detection of heat radiating from the human body.



## Localization

Localization involves sensing and/or computing the vehicle's pose (position and attitude). This is an extremely important function and has to be designed for high accuracy and reliable error detection. An extensive analysis of the area is given in [BoEv96]. In practice, many sensors are used simultaneously to determine the pose. Sensor fusion such as Kalman filtering is then used to compute a single best estimate of position and attitude. Three major sensor technologies are currently available [Reid98]:

### Dead reckoning

This class of techniques provides position and attitude information without relying on direct environmental sensing. Odometry uses wheel or shaft encoders measuring the rotation of wheels. By using the forward kinematic equations for the vehicle, the readouts from the encoders can be translated into displacements and rotational information. Unfortunately, odometry will be hard to use in forest environment. The tires are very soft and have a diameter that changes with the vehicle load. Also it is common with wheels slipping and sliding. Yet another problem is the non-flat ground that makes accurate forward kinematic equations very hard to derive.

Inertial navigation systems measure derivatives of the robot's position by gyros and accelerometers. Most equipment contains 3-axis pitch/roll/yaw gyros and 3-axis pitch/roll/yaw accelerometers. In this way attitude and position can be calculated.

### Machine vision

Terrain-navigation methods identify local features or landmarks in the environment around the robot and use these to aid in localization. The identification can for example be done with a ladar or a camera. By comparing terrain features with a constructed map, an estimate of position and attitude can be computed. Most reported applications have been using indoor robots [Cour93] but a few outdoor applications also exist [Durr96]. Vision data is often combined with other sensors to provide a global position and attitude information. More references can be found in [Durr01]. A method inspired by a *view-based* approach where images are stored in a database for look up and localization is described in [MaSa02].

In [JeCh01], information from a laser scanner and odometry is combined with a Kalman filter to form an estimate of attitude of the vehicle. In [SeHa01] a laser scanner is used to estimate relative movements that can be used for dead reckoning during GPS dropouts.

### Satellite-based triangulation

One of the easiest ways to perform localization is to use a high-quality GPS. Many advanced improvements of the basic idea of performing triangulation of radio-signals from a number of geo-stationary satellites

have been presented. Carrier Phase GPS, Dual frequency GPS and Kinematic DGPS are capable of delivering a position with errors between 2-20 cm and an attitude with an error of less than 0.1 degrees [Ocon96] [Reid98]. The situation in forest environment is not clear and has to be investigated. In any case, it is well known that there are serious limitations that make a GPS system insufficient as the single position sensor for an autonomous moving robot. It is therefore often combined with machine vision, INS or odometry in sensor fusion.

## Path tracking

Path tracking methods aim at keeping the vehicle approximately on a pre defined path, and bring it back to the path when unacceptable deviations occur. Various approaches for this task have been presented for AGV usage.

### Follow the carrot

One simple approach is known as follow the carrot (Figure 1). The name comes from the idea of holding a carrot in front of an animal to lure it into moving along the path. The carrot point is defined as the point on the path that is a look-ahead-distance away from the. The orientation error of the vehicle is defined as the angle between the current vehicle orientation and the line from the vehicle to the carrot point. The vehicle steering angle is then controlled such that the orientation error is kept as small as possible. A zero orientation error means that the vehicle is pointed at the carrot point. Several problems have been observed in practice. The vehicle cuts corners and there is also a tendency to oscillate about the path. Other methods have therefore been developed.

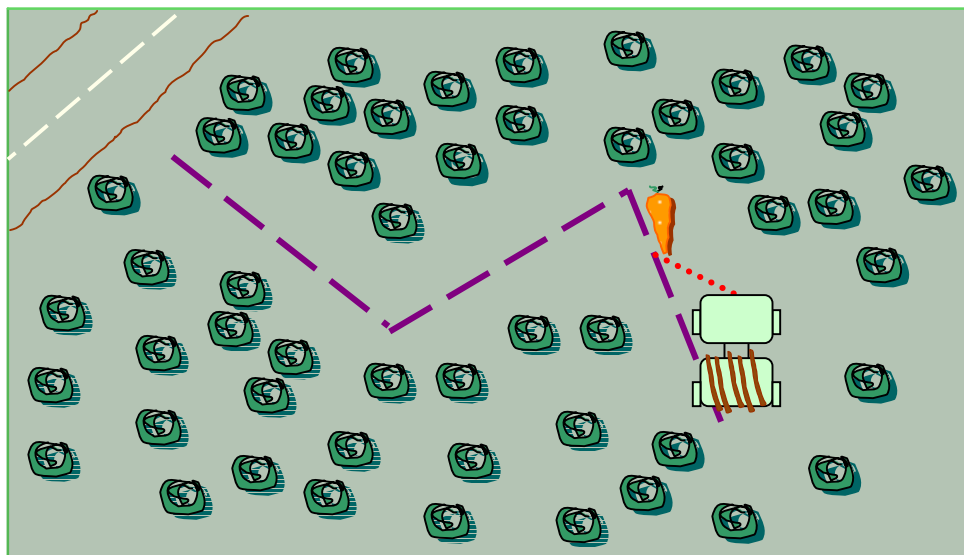


Figure 1. AGV following a path predefined by waypoints. Path tracking by “following the carrot”, a method causing the AGV to take shortcuts in sharp turns.

## **Pure pursuit**

Pure pursuit [ShSi91] uses a carrot point defined in the same way as for the follow-the-carrot method. A circle passing through the current vehicle position, through the carrot point, and parallel to the vehicle orientation at the current position is drawn. A PID controller then controls the steering angle with a set value equal to the curvature of the circle. This method works better than the follow-the-carrot technique for example when the vehicle is far off the path.

## **Vector pursuit**

Both the follow-the-carrot method and the pure pursuit method generate steering commands by only using the carrot position. At the carrot position, however, the orientation of the path is also known. The screw theory control technique works by attempting to not only have the vehicle arrive at the carrot point, but to arrive with the same orientation as the path. Screw theory was developed already in 1900 [Ball00] but was introduced in robotics somewhat later. In [Wit00], screw theory is utilized for a method named Vector Pursuit, which has been successfully used for path tracking in a number of different AGV systems.

## Obstacle avoidance

Obstacle avoidance is crucial for safe autonomous operation, and is considered to be the difficult part in this kind of construction of systems that operate in the vicinity of humans [Sten01].

Several well-known methods for obstacle detection have been proposed.

Potential fields [Khat85, KrHe95] is the classical approach where the desired heading of the vehicle is computed as the vector sum of repulsive and attractive forces associated with objects in the environment of the vehicle. The method was later combined with the concept of certainty grids [MoEl85], a mapping technique for sensor data accumulation and data fusion. The resulting method was named Virtual Force Field VFF [BoKo89]. Vector field histograms VFH [BoKo91] is an improvement using polar histograms with inverted distance information. Openings in the histograms indicate open areas for the robot to travel through. The robot velocity is chosen proportional to the obstacles. VFH overcomes the problems with local minima and instability associated with potential fields. Also, it recognizes the fact that a vehicle typically moves along arcs, rather than in straight lines. A further development, VHF+ [UIBo98], reduces some of the parameter tuning in VHF and also compensates explicitly for the robots width. The method is implemented and tested on the GuideCane, which is a guidance device for the blind. When the GuideCane encounters an obstacle, it steers around it. The VHF+ method is reported to give a more reliable and smooth trajectory than when using the unmodified VHF method. However, extensive testing of the algorithm showed that it sometimes made undesirable choices due to its local nature. The VHF\* [UIBo00] method uses the A\* algorithm to make the best choice by projecting the trajectory of the robot several steps ahead and evaluating the consequences.

The Curvature-Velocity Method CVM [Simm96] operates in velocity space rather than Cartesian space, and takes into account constraints in dynamics and assumes circular movements rather than linear ones.

Other techniques for obstacle avoidance are Elastic bands [QuKh93] and Nearness diagrams [MiMo00].

## 4. Target machines

The final target machine will be a standard forest machine, configured for the automatic computer control and for the need of sensors of various kinds. This is the most common approach to AGV design: simply automate an existing manual vehicle. To simplify things, many manufacturers provide an “automation option” on manual vehicles. E.g. Kalmar Industries (of Finland) who manufactures container straddle carriers and forestry logging equipment. Komatsu-Haulpack (large mining trucks and excavators) and Vost-alpine (underground mining equipment) also offer automation options for their products. However, in our case it will be necessary to install an automation interface since the plan is to use a standard forest machine from Partek Forest AB.

Some parts of the project can be run without access to a real forest machine. For this purpose a development robot should be purchased and installed in a “miniature forest” inside or outside the research premises.

Some parts, such as cameras or laser detectors, have to be mounted on the real target machine that can provide a realistic environment for development and testing. Of course, the final complete system will be also installed on a real forest machine and tested under real conditions.

### Forest machine

The system will be installed in a standard forest machine that has to be modified for the task. An outline for these modifications is given at the end of Section 5. The cost and work for the modifications are not included in the project budget.

It should be noted that the physical shape and layout of the target machine is tightly connected to the choice of sensors and also to the design of the control software. This means that the developed solution will have to be modified if and when another forest machine should be equipped with the system.

## Development robot

The project will benefit from an additional platform in development and testing, for the following reasons:

- It will increase the productivity of the development work since a full sized forest machine will need considerably more effort to access and use.
- The modifications of the forest machine are not trivial and can be performed in parallel with the development work.
- A lot of hardware and software will have to be purchased, learned and tested as part of the project. This work is most efficiently done in-doors, but need a reasonably realistic substitute for the eventual target machine

In addition to serving the goals of this project, a development robot will be useful since the research team will learn both hardware and software relevant for many future projects. The equipment can also be used for teaching robotics as part of IFORs aim at developing education in autonomous systems for off-road use.

The approach with a small-scaled robot is encouraged in [HaCa01], and also considered as a better alternative than computer simulation. After developing and testing on a small-scale robot, the systems can be transferred to the target vehicle, requiring much less modification than a simulated counterpart.

Two main alternatives for a development robot exist: buying standard equipment or having a custom designed robot constructed and manufactured. The latter alternative has the advantage of providing a platform that can mimic certain characteristics of the real forest machine that can be of value for the development work. This would for example be the construction of the steering device. The controller for a vehicle with articulated joint steering will differ significantly from the controller in a vehicle with a differential drive or with Ackerman (“car-like”) steering. Other important characteristic that is lost in a standard robot is the size aspects. The placement of sensors such as cameras or laser range scanners affects the behavior of the autonomous vehicle to a large extent. However, even a custom designed robot will differ significantly from the final target machine. Extensive work will therefore have to be performed on the target machine, regardless of the choice of development robot.

The advantage with buying a standard robot is first of all that it is available and works immediately (in a reasonably ideal world). A second advantage is that a range of sensor types with tested interfaces and drivers are available from the same supplier. A third advantage is that a ready built mini-robot also can be used in-doors for this project and also for other future projects.

The alternative with constructing and building a custom robot is not further considered in this report.

Regarding the second alternative, two suitable robots brands have been found: ATRV from iRobot Corporation [[www.irobot.com](http://www.irobot.com)] and Pioneer 2-AT, [[www.activrobots.com/ROBOTS/p2at.html](http://www.activrobots.com/ROBOTS/p2at.html)] from ActiveMedia Robotics.

iRobot Corporation develop and manufacture a series of standardized robots for both research and industrial use. The company's R&D lab is a division funded predominantly by the US government to develop "advanced mobility systems, intuitive user interfaces, multiple robot collaboration algorithms, embedded intelligence, dynamic programming environments, and machine learning algorithms". The ATRV robots (Figures 2, 3) have knobby tires, 4-wheel drive and water-resistant enclosure. The robots have a very comprehensive assortment of sensors and software and are commonly used by other research groups. The physical ATRV robot is very rugged and comes in two sizes: 105cm and 77.5cm long. A laptop computer is mounted inside a tight compartment and runs a Linux based system Mobility, that can be used a basis when developing the software for the project. A radio Ethernet connection can be used to communicate with another computer. The sensor assortment includes e.g.: six different camera systems, two types of SICK® laser scanners, compass, Inertial Navigation Sensor (INS), Orientation sensor, 12 channel GPS.



*Figure 2. The ATRV from iRobot. HxL:65cm x 105cm. Weight: 118kg. Photo courtesy of iRobot Corporation.*

iRobot Corporation ATRV (prices in USD excl. custom):

ATJR <b>ATRV-Jr Mobile Robot System</b> – Includes: Robot, Basic Sonar Suite, Onboard Computer, Charger	23950
ATMI <b>ATRV-Mini Mobile Robot System</b> – Includes: Robot, Basic Sonar Suite, Onboard Computer, Charger	(9950)
MSIS <b>Monochrome Stereo Imaging System</b> – Includes: Black and White Camera Board, PCI Frame Grabber, Mounting and Wiring and Mobility Support	3960
SVSY <b>Small Vision System</b> – Includes: WATEC Black and White Camera, PCI Frame Grabber, Mounting and Wiring and Mobility Support	3685
DGPS <b>Differential GPS System</b> – Includes: Base Station, Mobile Unit, Antennas	11440
AOSR <b>Absolute Orientation Sensor</b> – Includes: Compass/Tilt Sensor	2420
COMP <b>Compass</b> – Includes: Electronic Compass	1595
INSY <b>Inertial Navigation Sensor</b>	4400
FOGY <b>Fiber Optic Gyro Sensor</b>	4300
BUMP <b>Tactile Bumpers</b>	900
1SYS <b>Wireless Radio Ethernet 1-Port System</b> up to 3Mbps	3410
CHRG <b>Charger</b>	1250
BATT <b>ATRV-Jr Batteries</b>	450
TOTAL USD with academic discount 10%	34029



Figure 3. The ATRV-JR from iRobot. HxL: 55cm x 77.5cm. Weight: 50kg. Photo courtesy of iRobot Corporation.





Figure 4. Pioneer 2-AT from ActiveMedia Robotics. HxLxW: 26cm x 50cm x 49cm. Weight: 30kg. . *Photo courtesy of ActivMedia Robotics.*

The Pioneer 2-AT (Figure 4) from ActiveMedia Robotics is smaller than the ARTV robots. It has an on-board micro controller for motor control and low-level access to sonars and bumper switches. For more computing power, an additional computer can be placed on-board or connected via a wireless radio modem. The ARIA software contains utilities for development of systems and the Saphira software contains high-level utilities for path planning, localization with sonar and laser.

The sensor assortment includes five different camera systems, one type of SICK® laser scanner, Inertial Navigation Sensor (INS), Orientation sensor, 3 types of GPS Receivers, sonar sensors and bumpers.

## Academic Prices Pioneer 2-AT (prices in USD excl. custom):

P2T0001 <b>Pioneer 2-AT Mobile Robot</b> Base Pioneer 2-AT Mobile Robotic skid-steer base w/ 4 drive wheels, micro controller, motors, encoders, 1 battery, std. Pioneer software & no sonar, ARIA/Saphira	5995
ACT0007 On-Board VS8 <b>Computer</b> Onboard 800 MHz VERSALOGIC8 PC with PC104+ bus, 128 MG RAM, 2.5" 10 GB hard drive,	2575
SOF0004 <b>LINUX</b>	195
BASIC SUITE PRO: NavigatorPro & MapperPro <b>Software Suite</b> allows plug-n-play laser mapping on-the-fly, laser navigation, localization, map editing, keep-off areas, goals, action sequencing & scheduling, plus tele-op & Net operation	2995
ACT0037 <b>Manual-Tilt camera</b> , PCMCIA frame grabber, color-tracking	(1890)
ACA0096 <b>Manual-tilt Color Digital Stereovision</b>	5495
ACT0080 <b>20cm Accurate GPS</b> System Novatel 12 channel GPS receiver, 20cm accuracy 70% of time	21995
ACT0078 <b>1m Accurate GPS</b> System Novatel 12 channel GPS receiver, 1m accuracy 70% of time	(13995)
ACT0089 <b>Inertial Correction System</b> Inertial Measurement Sensor with Rate Gyro & Magnetometer	2495
ACAT031 <b>Front Sonar Ring</b>	375
ACAX013 <b>Bumper Pair</b>	945
ACT0075 <b>20deg POSITION SENSOR</b> electronically gimbaled ferrous-compensating position sensor	1295
ACT0036 <b>High-Speed Wireless Ethernet</b>	945
ACT0073 <b>High-Capacity Charger</b>	280
ACT0061 <b>Additional memory</b>	238
ACT0008 <b>On-Board Computer integration pack</b>	565
TOTAL USD	46388

It should be noted that the price lists given above for the iRobot and the 2-AT robot not necessarily contain comparable items. To make a fair comparison, the offers and the specifications of the products have to be examined in more detail. This is also suggested as one of the first sub tasks in the project plan (Section 6).

## 5. Preliminary System Design

### System overview

A block diagram of the suggested system design is shown in Figure 5.

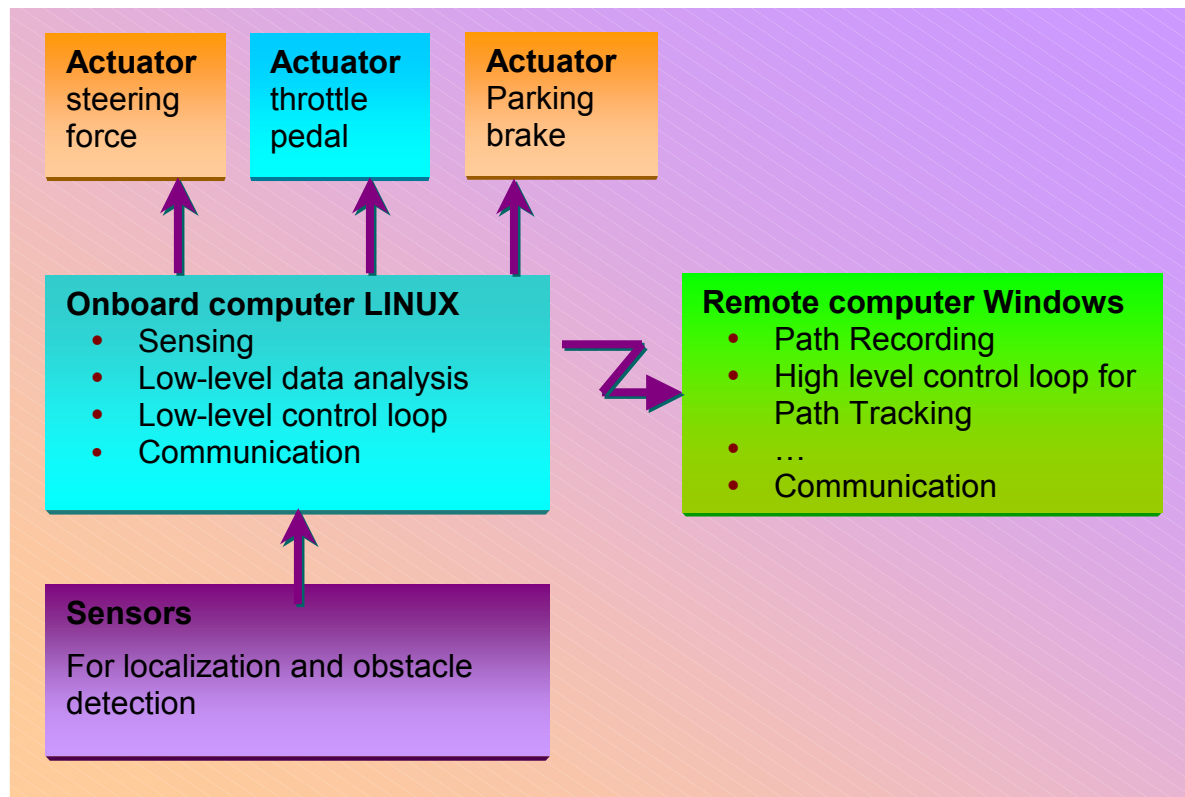


Figure 5. Block diagram of the complete system

The onboard computer senses the environment and performs low-level pre processing of sensor data. Time critical image analysis may also be done here. Other tasks might be sensor fusion of GPS and INS to compute the location and attitude for the vehicle. Also, code for low-level control of the wheel rpm and steering angle is placed in this computer. The radio-Ethernet connected PC computer is used for the rest of the system. In the Path Recording mode, the operator drives the vehicle along the desired path. Locations, speed and turning angles are recorded in the computer. The control loop for path tracking is responsible for providing set values to the controllers for steering angle and wheel rpm. The vehicle is autonomously controlled by the computer, which guides the vehicle along the recorded path while avoiding obstacles. Obstacles in front of the vehicle are detected by various sensors such as cameras and infra-red detectors. Obstacles appearing as a consequence of the vehicle deviating slightly from the path are avoided by steering corrections. Obstacles that are suspected to be human beings cause the vehicle to halt and alert the human operator. The operator may then command the system to resume the autonomous operation or to drive the vehicle manually. The hardware

and software involved in the design will be described in detail in the following two sections.

## Preliminary hardware design

This section outlines a preliminary design of the hardware required for the project. The overall design is shown in Figure 6. The main ingredients will be described in more detail below.

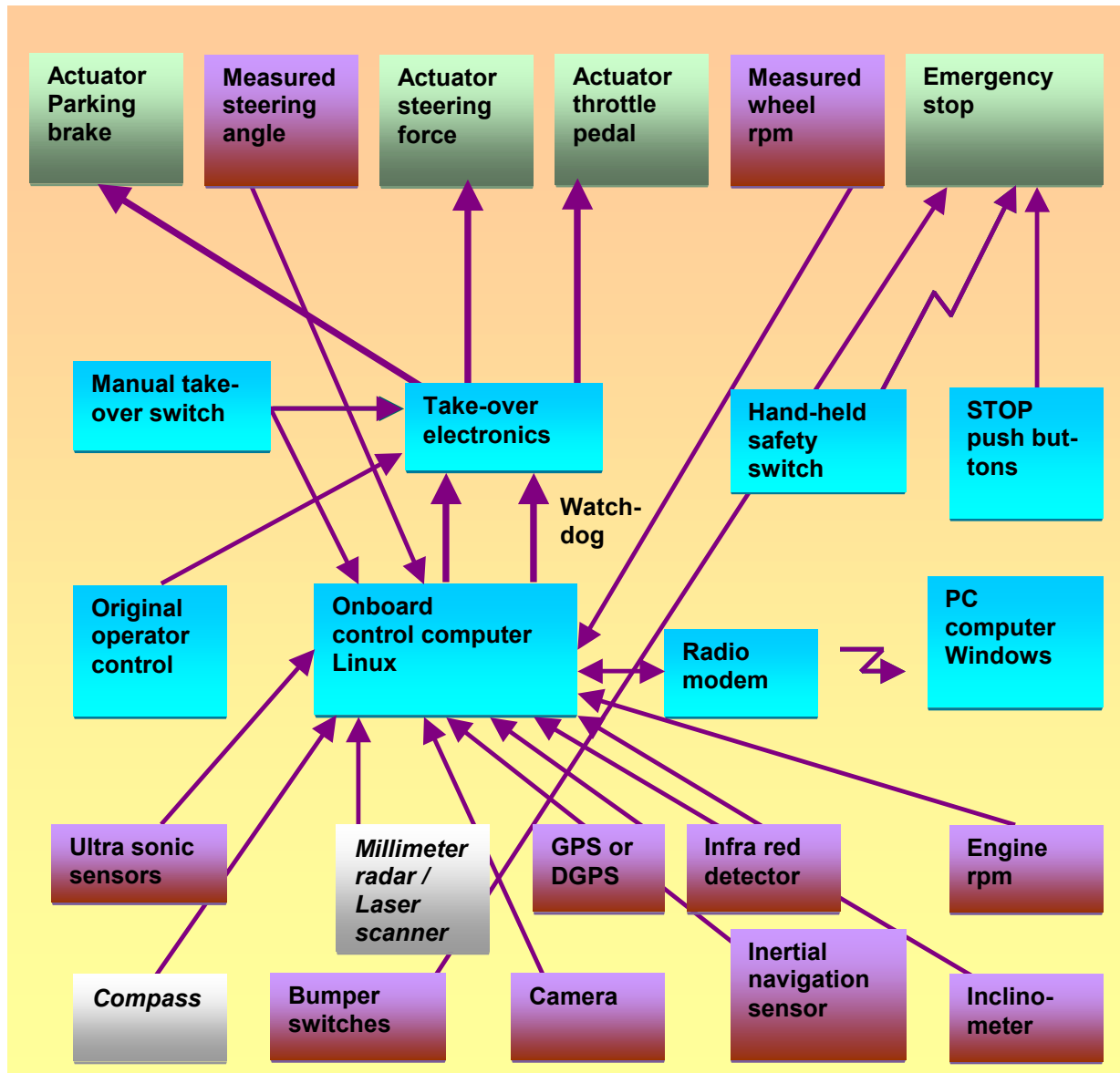


Figure 6. Block diagram of the hardware design for installation in a modified forest machine. The directions of the arrows indicate flow of data. Bold arrows are used for control signals and thin arrows are used for sensor signals. Boxes with text in *italics* indicate components that are judged not to be immediately necessary for the operation. However, they should be considered and evaluated as part of the project.

## Sensors

Section 3 describes the operation of the various sensor types. Their function in the proposed design shown in Figure 6 is as follows:

- GPS is used for localization, i.e. determination of the vehicle's position and attitude and possibly speed. Compass may provide additional attitude information. However, they are known to be of limited value close to large metal objects and machine equipment.
- INS is also used for localization in combination with GPS. It may also be used for detection of collision with stones and trees.
- Ultra-sonic sensors are used for obstacle detection.
- Infra red detectors can be used to detect human presence.
- Camera can be used for obstacle detection and also localization. Stereo or single camera systems are possible choices.
- Millimetre wave radar and Laser range scanners can both be used for accurate detection and mapping of the objects around the vehicle. This can be utilized for obstacle detection and also for localization. Since laser scanners are known to be sensitive to rain and dust [Sing97], the alternative of using millimetre wave radar should be seriously investigated.
- The Inclinator is used to prevent hazardous movements that may jeopardize the stability of the vehicle.
- Engine rpm, Measured wheel rpm and Measured steering angle provide necessary feedback for the low-level control of speed and steering.
- Bumper switches are an important safety function. They should be connected to the Emergency stop of the vehicle in such a way that they cause the vehicle to halt immediately if activated. Hitting an obstacle physically should not happen if the vehicle's perception system is working properly. If it does happen, it indicates the uncertainty about the state of the world is too high to allow continued operation. However, the harsh environment for a forest vehicle in operation may make the task of mounting bumpers and delicate switches extremely difficult.

The applicability of these and other sensors in forest environment should be investigated thoroughly. In particular, the operation of GPS in forest environment should be investigated.

## Computers

The computing power may be divided in two parts as shown in Figure 6. An onboard computer with Linux operating system is responsible for the low level communication with the sensors and actuators. Computer intensive image processing could also be implemented on this computer. The software should be written in C or C++. The other computer may be Windows based and runs programs written in any language, e.g.: Matlab or Java. Such a distributed architecture is often used for AGV designs and is encouraged by the software delivered with the Pioneer 2-AT robot described above. The disadvantage with two computers are mainly of practical nature and is balanced by the advantage of developing parts of the system in a more user friendly environment than Linux and C programming. The exact division of routines on the two computers is left for later decision. In one extreme, the onboard computer does nothing but sensor handling and low-level actuator control. The sensor data is placed in a data structure that is made available to the remote computer through the radio Ethernet connection. This would be an advantageous situation, since programming and debugging are hard to perform on the moving vehicle, be it the min-robot or the final forest machine. The speed of the radio-modem supplied for the Pioneer 2-AT robot is 85 Kbps. The ATRV system offers a radio Ethernet modem with up to 3Mbps, which should be enough even with the image analysis placed on the remote computer (there is an Ethernet modem available for the 2-AT too).

### Software watch-dog

To safeguard against interrupted communication and also unexpected delays in the remote computer, a “software watch-dog” should be incorporated. The onboard computer should constantly monitor the communication with the remote computer (ping/pong) and temporarily halt the vehicle (set speed to zero) if delays occur. In this way absolute real-time performance for the remote computer is not be absolutely necessary. A longer delay in the communication with between onboard and remote computer should cause the onboard computer to activate the hardware watch-dog which switches control from computer to operator control.

## Emergency stop

The emergency stop is connected to the ignition of the engine and causes the vehicle and engine to come to a complete stop when activated. This means that the entire vehicle will have to be manually restarted to commence operation. The emergency stop is connected to buttons placed around the rim of the vehicle and also to the bumper switches. The emergency stop is also connected to a handheld safety switch through a separate radio link. This switch should be designed such that an operator always has to hold a button pressed down to prevent the emergency stop from being activated.

## Control and actuators

The computer control will be inserted between the existing manual operator controls and the existing control computer that governs throttle position and increase/decrease of steering joint angle. It should contain the following functionality:

### Take-over electronics

One important part of the design is the take-over electronics that controls the switching between manual and computer control. The onboard computer requests control by setting a digital input TAKE OVER to *true*. The control of vehicle speed and turning angle will now move from the operator controls to the onboard computer. A manually operated switch has to be in ON position to allow the computer to take over, and it can at any time be switched to OFF position and thereby move control back to the idle. The electronics should also sense a hardware watch-dog output from the onboard computer. It operates by periodically (~1-10Hz) transmitting an electrical signal that resets a timer inside the take-over electronics. If the signal is not sensed for a certain preset time (~0.1-1 sec.) the control is electrically switched back to the operator control, which corresponds to zero speed and unaltered steering angle.

### Wheel speed and steering control

During operator control, the propulsion of the vehicle is controlled by the throttle pedal. This signal is switched over to the onboard computer by the Take-over electronics as described above. A wheel speed controller should be implemented on the onboard computer. This controller takes a set value for wheel speed and controls the throttle with the signal *Measured wheel rpm* as feed back signal. Note: this controller also introduces a source of possible problems. The vehicle may behave more predictable if the higher levels of the system control the throttle directly, without any wheel rpm controller in between.

Control of the steering angle should in a similar way be interfaced to the computer. The controller has to be somewhat different from the speed case since the signal *Actuator steering force* works as an increase/decrease signal controlling the articulated joint that is used for the steering of the vehicle. The controller could therefore be a pure proportional controller, since the integration part is done in the hydraulics in the joint itself. The *Actual steering angle* is sensed and fed back to the control loop.

### Parking brake

The parking brake should be automatically activated if the wheel speed controller issues a zero speed signal and the vehicle has not come to a complete stop within a predefined period of time (typically 0.x second).

## Preliminary software design

This section outlines a preliminary design of the software required for the project. Some of the components have been extensively studied in previous research and in these cases a review of existing solutions will be given. Most components will involve a lot of research and development work. Important issues will in these cases be suggested for further investigations as part of the project.

The overall design is shown in Figure 7. The main modules will be described in detail below.

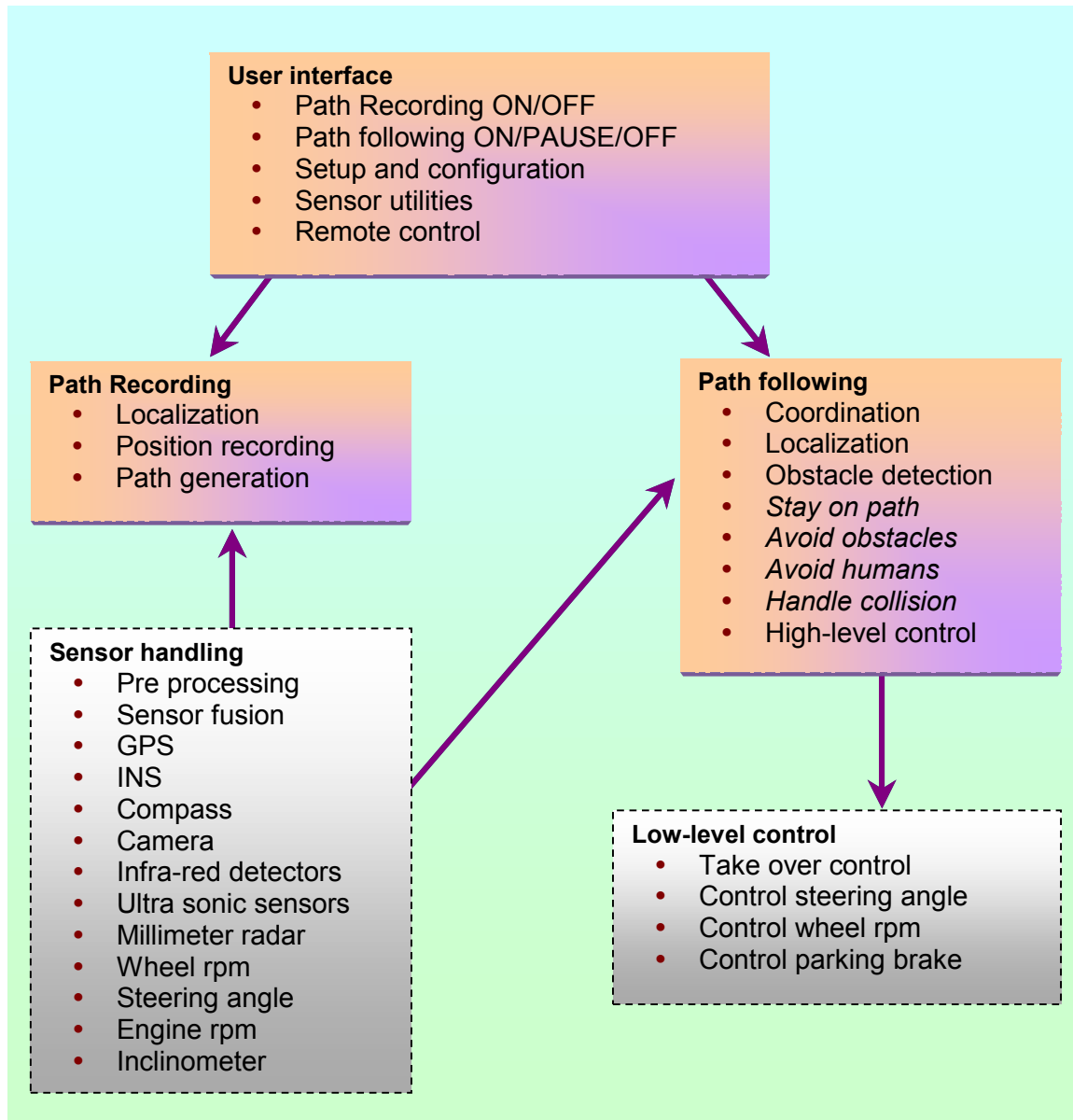


Figure 7. Block diagram of the overall software design. The arrows indicate flow of control. The dashed blocks should be implemented on the onboard computer while the others preferably should be implemented on the remote computer.



## User interface

Contains function to control the various parts of the system. Some functions are implemented to facilitate development and testing. Certain important user interface issues relevant for the end product will also be implemented and evaluated. The user interface should be implemented in the remote PC that communicates with the onboard computer via radio modem. The following commands and functions should be implemented:

### Path Recording ON/OFF

The recording of position, attitude, steering angle and speed should be initiated.

### Path Following ON/PAUSE/STOP

The stored path should be autonomously tracked while avoiding obstacles. The following functions should be implemented: ON/PAUSE/STOP.

### Setup and configuration

All parameters and options for the developed system should be easily modified in a windows-based configuration system.

### Sensor utilities

- Logging - All or selected parts of sensor data should be logged for analysis and documentation.
- Graphic display - Sensor data should be viewable in various graphical forms to aid in the development work
- Statistics
- Export of data - The sensor data and also logged records of autonomous driving should be exportable to other programs for analysis.

### Remote control

Low level control of wheel rpm and steering and of the controllers described in the Section *Control and Actuators* above. Useful for testing and debugging during the development work. Also useful for a tele-operation mode, for remote direct control of the vehicle. Should include the following functions:

- Set throttle position
- Increase/decrease of the steering angle
- Set speed for the wheel speed controller
- Set steering angle for the steering angle controller
- Activate/deactivate parking brake
- Control of the take-over electronics (the TAKE OVER signal)

## Path Recording

After initiating this mode, the human operator manually drives the vehicle along the desired path. The position, attitude, steering angle and velocity is constantly recorded and stored in the onboard computer. When the path is completed, the operator switches off the recording. The recorded path should now be compressed and stored as waypoints connected by linear or possibly circular segments.

The path recording depends heavily on a correct estimate of the vehicle's position and attitude, i.e. Localization. This issue is covered in the next section since it is also part of the Path-following.

## Localization

Localization involves sensing and/or computing the vehicle's pose (position and attitude). This is an extremely important function and has to be designed for high accuracy and reliable error detection.

The basic sensors for localization are GPS possibly enhanced by sensor fusion with an Inertial Navigation System (INS). Even with good conditions. GPS routinely fails for periods of time. However, these periods are most often short and a useful strategy for the current project might simply be to halt operation until the GPS signal is reliable again. The technique is used in [PiHa99] where the authors report typical lengths of dropouts being between 30 and 120 seconds. For a test period of 13 hours, only five such dropouts occurred. It is not clear if this method of simply stopping will work in dense forest if the dropouts are caused by the trees blocking the signals from the satellites.

[SeHa01] describes a method with laser images where the polar readouts from a laser scanner is transformed to cartesian coordinates and inserted in a map. This map is then compared to the map from the next laser scan. By finding the optimal translation and rotation that makes the two maps overlap, the translation and rotation of the vehicle can be estimated. This estimate can be used for dead reckoning during GPS dropout periods.

Odometry is of limited value in this application for a number of reasons: the ground is definitely not flat and the diameter of the tires vary depending on the load and air pressure in the tires. Furthermore, adding wheel encoders on a standard forest machine in a stable way will be very costly. One idea for research would be to try to build algorithms for adaptive dead reckoning based on steering angle and wheel speed. The model, e.g. a neural network, would be used to map speed and angle to a displacement vector and a rotation. If this mapping could be dynamically updated in real time, the estimated values could be used for dead reckoning during GPS dropouts.

## Path Following

Path Following is the major module where the autonomous functions of the vehicle are executed. The vehicle should follow the path defined in the previously described Path Recording mode. Safe operation includes tight tracking of the path as well as detection and avoidance of obstacles. In particular, new obstacles appearing on the path should be regarded as potential human beings and should cause the vehicle to enter a halt mode, awaiting manual assistance. However, in tight passages trees or stumps might appear as obstacles and should then cause a change in course rather than causing a complete stop of the vehicle. This shouldn't happen if the vehicle stays on the path, but can easily occur when the vehicle slides away from the path due to errors in the localization or other disturbances.

The general design is behavior-based with four major behaviors: *Stay on path*, *Avoid obstacles*, *Avoid humans* and *Handle collision*. These behaviors have opinions (sometimes contradicting) about how the vehicle should move in order to fulfill the object of the respective behavior. The opinions are merged in the Coordination module as described in Section 3.

The behaviors rely heavily on correct information regarding the vehicle's pose (position and attitude) and also about the environment close to the vehicle. The former task is covered in the Section *Localization* while Obstacle detection is covered in the next section.

## Obstacle detection

Detecting obstacles implies an active perception of the environment. Three main classes of obstacles are important to detect and distinguish between:

- Human beings:  
Since humans never should be allowed in the vicinity of a running vehicle, the detection task could be somewhat simplified. It is not necessary to know the position of the human, detecting its presence close to the vehicle is sufficient.
- Navigational obstacles.  
This class of obstacles refers to objects that call for maneuvering the vehicle in order to avoid collision. This includes objects such as trees, stumps and stones. The location of the obstacle should be determined such that the *Avoid-Obstacle* behavior can prevent collision while still proceeding along the path. One big problem is the cluttered environment the forest vehicle is operating in. Bushes and small trees will constantly get in the way of the vehicle, even during normal operation. Distinguishing between these harmless obstacles and "real" obstacles such as thick trees, stumps and stones is a great challenge for the development work.

A number of sensor techniques can be applied to this area of obstacles detection: Ultrasonic sonars are useful to distinguish between free and

occupied space in front of the sensor but have too low resolution to identify the exact location of the obstacle. Color segmentation of images should also be considered. In [Olli97, PiHa99] such classification is used to distinguish between cut and uncut crop for an autonomous harvester. In the same way, it would be possible to classify pixels as either belonging to a human being or not. The possibility to use infra-red sensors (burglar alarms) to detect humans should be investigated. Using a microphone would be another unconventional method.

- Colliding objects.  
The detection of large trees and stones will at least occasionally fail and the vehicle will hit the obstacle. This is important to detect since the situation should trigger the *Handle collision* behavior described below. Suitable methods to detect a collision have to be investigated. One possibility is to use the inertial navigation system (INS) since a collision normally involves heavy retardation that might be measurable. A collision may also cause the wheels to spin. This could be detected by monitoring the vehicle's displacement (also by using the INS) in relation to the wheel speed. The inclinometer and engine rpm may also be helpful in this difficult and important task.

A lot of research has to be invested in the area of obstacle avoidance to achieve safe operation in all possible light and weather conditions. One extra problem with the application is the problems involved in safely mounting devices on the forest vehicle. The only realistic place for sensors is probably inside the cabin since they would otherwise be severely damaged or simply ripped off by the close-encounter with the surrounding vegetation.

### **Stay on path behavior**

This behavior contains functions that keep the vehicle approximately on the path, and bring it back to the path when unacceptable deviations occur. A number of standard techniques for this task are described in the Section *Path Tracking*. A number of special conditions might call for special solutions and development in the area of path tracking and control algorithms:

- How does the articulated joint steering affect the operation of the algorithms?
- The Path Recording does not only record position, but also attitude, steering angle and speed. How can this information be utilized to improve the *Stay on path* behavior? One idea is to use the recorded steering angle as a constant offset at each location. In this way, the path tracking problem gets linearized and the controller will only have to make minor adjustments to keep the vehicle on the track.
- Does an empty vehicle's behavior differ significantly from a loaded one? In such case, should separate paths be recorded?

### **Avoid obstacles behavior**

Once an obstacle has been detected in front or close to the vehicle an appropriate action has to take place. The exact strategy for this has to be developed. Obstacles appearing on what is assumed (according to the recorded path) to be free path should cause the vehicle to stop and await human guidance. Obstacles that are caused by the vehicle being temporarily off-track should allow the vehicle to adjust the steering angle and continue to follow the path. A number of available methods for obstacle avoidance are described in the Section *Obstacle Avoidance*. How the constrained moveability and large size of a forest machine affect the methods has to be investigated.

### **Collision handling**

It is necessary to include a behavior to handle actual collisions, since the obstacle detection system at least occasionally will fail and the vehicle will hit a large tree or stone. The best design of this behavior has to be further investigated. A first approach is to simply stop the vehicle and alert the operator for assistance.

### **Avoid humans**

The safest and easiest way to design this behavior is to stop the vehicle and alert the operator for assistance. This might also be the correct approach, since human beings should not be allowed in the vicinity of a forest machine in operation.

### **Other behaviors**

The *Stay on path*, *Avoid Obstacles*, *Collision handling* and *Avoid-humans* will be implemented in a behavior-based architecture. More behaviors can easily be added if needed. A *Start-up* behavior and a *Finish* behavior are examples of behaviors that should be included in a complete autonomous vehicle as part of the long-term vision (See Introduction).

## **High level control**

As soon as a heading direction, and sometimes also a speed, has been suggested by the path tracking algorithm, it has to be executed. This control stage is sometimes included in the path tracking algorithm (e.g. the basic pure pursuit algorithm includes as a PID controller). In the general case, the controller is a separate device that can be constructed using a number of techniques. The conventional approaches in classical control are proportional-integral-derivative control (PID), adaptive control and state-space methods. Some newer techniques include fuzzy logic and neural networks. A fuzzy controller is combined with the Vector Pursuit method in [Wit00].

Areas to be further investigated include:

- How to control speed in sharp slopes and turns
- How to detect and handle traction failures
- How to minimize stability problems (risk for tip-over)

## Low-level control

The forest vehicle provides control of throttle pedal for vehicle speed and steering force for steering angle. The throttle speed is used in a PID controller for vehicle speed. The *Parking brake* is used as a safety measure when the system issues a zero speed command. If the PID controller has not managed to bring the wheels to a complete stop within a certain period of time (typically 0.5 seconds), the parking brake should be activated (an alternative approach is that the parking brakes should always be activated 0.5 seconds after a zero speed command has been issued).

The steering angle is controlled by a PD regulator controlling the *Actuator steering force* signal. This signal acts as an increase/decrease signal to the steering joint. A zero values means unaltered steering angle.

The control parts have to be carefully designed, since it operates the steering, propulsion and main engine of the vehicle. Security aspects as well as running conditions for the engine have to be in constant focus. Areas to be further investigated include:

- What limitations (min/max, rate of change) exist?
- How should end-positions for the actuators be handled?
- How should other safety aspects be handled?

## Sensor handling

The sensors provide information about the state of the vehicle and the world around the vehicle. The same sensors are often used for many purposes (e.g. the wheel encoders are both used for dead reckoning and to detect slippage) and multiple sensors are often used for one single purpose (e.g. GPS and INS are fused to give a better estimate of position). The standard way to perform sensor fusion is Kalman filtering [Kalm60, DuJe00]. It computes an optimal (under certain conditions) weighted sum of many inputs to form a fused value from many signals. A critical part of the algorithm uses the covariance matrix for the input signals. This matrix is also used to compute the confidence in the estimates. One problem with Kalman filtering is that it assumes a pretty ideal sensor model for the noise. An alternative is to use a neural network to learn the optimal relation between sensed data and the actual physical entity. In [Thru93], two networks are suggested: One for the sensor mapping and one to give an estimate of the uncertainty in the first network.

Sensor handling also includes low-level filtering and outlier detection of noisy sensors. In the proposed system design, the onboard computer should be responsible for the low level sensor handling and present a data structure with the latest estimates to the remote computer through the radio modem. If judged advantageous, parts of the data analysis such as filtering and image processing can also be included in the onboard processing.

## Software Development

The development work should obviously aim at producing software that will run on the eventual target machine. However, to speed up and increase the potential quality of the end product, alternative development platforms may be used during the development and research phase. The development of image analysis algorithms may very well be done using Matlab. Series of test images can be shot and used for extensive “off-line” work with obstacle detection, human detection and localization. The developed algorithms should then be translated to the chosen run-time environment and tested under real-time conditions.

If the suggested hardware architecture with an onboard computer and a radio Ethernet connected remote computer works out well, the development work will be greatly simplified and speeded up.

## Simulation

Simulation is often used as part of the development work for autonomous vehicles and robots in general. However, it is commonly believed that the physical interaction between robot and environment is not possible to simulate in a sufficiently accurate manner. An attempt to model the physical interaction between wheels and ground and also the robots dynamics is done in [ChLa95, Chlb99]. The results are not transferred to a real robot for verification.

The major reasons why simulations of out-door robots encounter problems are [HaCa01]:

- Numerical simulations do not usually consider all physical laws of the interaction between robot and environment, such as mass, weight, friction, inertia, etc.
- Physical sensors are noisy and actuators have uncertain effects. This is seldom modeled in simulation since it requires exact knowledge of the nature of all these uncertainties.
- Physical sensors and actuators differ because of wear and tear, differences in manufacturing, differences in their position on the robot and because of varying weather or environmental conditions.

The first decade of robotics research did indeed try to model the complete interaction robot/environment in the Sense-Plan-Act paradigm, with limited success. Despite this, many robotics researchers regularly use simulation to test their algorithms. However, the validity of such simulations is often criticized and is the subject of much debate. Adaptive systems, developed with simulation, usually fail when they are transferred to the real out-door world [MiLu95].

Higher-level behaviors are often successfully developed using simulation techniques. These include path following, obstacle avoidance, task planning, stability issues and control system design. For the current project, it would be of great value to simulate steering

control (operating a vehicle with articulated joint steering), path tracking and obstacle avoidance. A simple simulator for these purposes could be written in Matlab or Java as part of the development work.

## **Modifications of the forest machine**

The following functions has to be implemented in the standard forest machine to facilitate control and sensing (some of them are described in more details in the previous section):

- “Take-over” unit that transfers control from the operator controls to the computer system
- Inputs for control of throttle pedal
- Inputs for control of steering force
- Input for activation of parking brake
- Emergency stop function
- Hand held emergency stop switch with radio communication
- Mounting of sensors such as cameras, GPS, INS, compass, inclinometer, etc.
- Mounting buttons for emergency stop
- Steering angle signal
- Wheel rpm signal
- Engine rpm signal



## 6. Project Plan

At this early stage no detailed project plan can be presented. The basic project plan is:

1. Start-up phase with purchasing and learning of equipment, more extensive studies of previous work in the area and establishment of contacts useful for the projects.
2. Concurrent research/development of sub-projects (see list below)
3. Tests on development robot and forest machine
4. Modification of forest machine
5. Integration and testing on forest machine
6. Evaluation and reporting

Like most development projects, steps 2-5 will be iterated until a satisfactory result has been achieved.

### Time Schedule

The proposed project involves a lot of initial work since it is the first autonomous robotics project within IFOR. The total time is estimated to two full years with the following time schedule serving as a preliminary plan for the work:

Activity	Year 1A	Year 1B	Year 2A	Year 2B
Case studies/visits	◆			
Development/research	◆			◆
Inst. and tests new equipment	◆	◆		
Installation on mini-robot		◆		
Testing on mini-robot		◆	◆	
Installation on forest machine		◆	◆	
Testing on forest machine		◆		◆
Report writing			◆	◆
Project management	◆			◆

## Sub projects

Most of the issues covered in the sections above can be defined as separate sub tasks within the total project.

### Initial projects

- Evaluation and selection of development robot
- Evaluation and selection of development environment
- Buying, installing, testing and learning new equipment

### Development and research projects

Most of these tasks are suitable for doctorand/master projects, either by itself or combined. These are written in bold in the list below.

- **User interface with setup, configuration, sensor analysis, remote control of vehicle and high-level system control.**
- **Evaluation of sensors in forest environment**
- **Development of sensor interface/low level control interface and communication protocol**
- **Path Recording**
- **A simulator for high-level simulation tasks**
- **Obstacle detection**
  - Navigational obstacles (small trees, stones, etc.)
  - Colliding objects
  - Human beings
- **Localization**
- **Sensor fusion**
- **Use of machine vision or ladar**
- ***Stay on path* behavior**
- ***Avoid obstacles* behavior**
- ***Avoid humans* behavior**
- ***Handle collision* behavior**
- **Other behaviors**
- **Coordination of behaviors**
- Modifications of forest machine
- Construction of take-over electronics

## **Administrative and meta-projects**

In addition the essentially technical, tasks mentioned so far, a number of administrative and meta-project tasks are identified:

- Project management
- Work with the overall system design
- Development and testing procedures
- How can the individual modules be developed and tested?
- When can simulation be used?
- When can the small sized robot be used?
- When is it necessary to use a “real” forest machine?
- How should the transfer from development robot to forest machine be simplified?
- Adherence to the long-term product goal
- Safety issues. Overall coordination and general analysis (e.g. is sensing behind the vehicle necessary?)
- Which domain specific problems may occur?

## **Industrial partner**

The implementation of the system in a real forest vehicle requires an active collaboration with Partek Forest AB, the manufacturer of the machine. A formal agreement with the company should therefore be signed.

## **Resources**

Deciding who will be involved in the project obviously has to be discussed at an early stage. More specifically, the following issues should be discussed:

- Estimation of time for the different sub-parts of the project
- Who can do the job?
- In which parts can doctorands and master students contribute to the project?
- Additional resources: contacts with other research groups, choice of equipment.
- Where should the practical parts of the projects take place?

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