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VISION-BASED NAVIGATION OF THE NOMAD XR4000 MOBILE ROBOT

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***Abstract**. This work presents the steps for the development of a vision-based navigation system for the Nomad XR4000 mobile robot. The system is composed by several modules that are responsible for a small set of tasks: image capture module (camera and framegrabber); image pre-processing module (noise reduction, feature extraction and object recognition); motion detection module (analysis of images to get data from the motion of the surrounding objects); and the robot's control module (generating robot's motion commands from the visual and sensorial input data). This system is aimed to track an object by visual sensing, and avoid static obstacles using its others sensors (infrared, for near objects; and ultrasound, for far objects).*

***Keywords**: Machine vision, mobile robots, vision-based navigation.*

1. INTRODUCTION

The machine vision technology has been growing at fast rates, impulsed by industrial application like product inspection and pattern recognition as well as by academical research made in several institutes. This boom is mainly the result of the recent personal computer explosion in performance, in which a simple desktop PC can handle millions of operations by second at relatively low costs. This cost reduction and performance increase brought the return of several processing demanding tasks, like machine vision and correlates.

Robotics is another technology in which the computer revolution gave new perspectives in development. The new robotic systems are cheaper and faster, light and small, giving to the designer a full set of choices to define a better robot to a defined task. Uses of robotics includes welding, painting and material handling, and today the development of mobile robotics is bringing a larger set of possibilities.

Figure 1. Vision based welding at GRACO (Alfaro, 1999).

Machine vision and robotics are getting closer day by day. The use of vision systems in welding and mobile robotics can increase the knowledgment of both fields. Robotics gains with a powerful sensing device and vision is challenged with new tasks. The work of Alfaro, et al (1999) presents the use of a vision system as an auxiliary sensor to the welding robot IRB 2000 (see fig. 1).

This work aims at using machine vision to implement the main navigation sensor of a mobile robot. The system will be defined in several modules, each one coping with a small set of tasks. The system aims at robustly control a mobile robot in a changing environment, based on the motion of an object in the robot's surrounding..

2. THE XR4000 MOBILE ROBOT

This section presents a small description of the features of the Nomad XR4000 mobile robot.

2.1. Sensors and Actuators

The Nomad robot carries two types of non vision-based sensors, namely the ultrasound and the infrared position sensors. The robot also supports a color CCD camera as part of the vision system hardware. The ultrasonic (see fig. 2) and the infrared arrays of sensors are appropriate to detect the object position in long and short range distances, respectively. The motion system of the robot is based on four wheels, each controlled by two motors, having two degrees of freedom each. The robot has fully holonomic motion, moving on the floor plane in the three allowable degrees of freedom (translation and rotation) at any time. This type of motion is adequate to accomplish a required task on a plane surface.

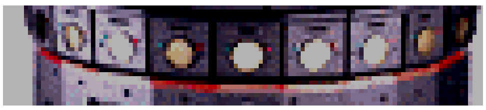

Figure 2. Ultrasonic ring of XR4000 robot.

2.2. Vision System

The onboard vision system of the robot is based on a Matrix Meteor card and a Hitachi camera. The camera can change its orientation in the robot's frame by means of a pan-tilt device, that permits up to 300^o pan rotation and up to 60^o the tilt one. The system is integrated with the robot's programming libraries (C language) and can be accessed by an user program. Fig. 3 shows the camera and the pan-tilt unit of the robot.

Figure 3. Pan-tilt unit and the robot's camera.

3. COMPUTER VISION IN MOBILE ROBOTICS

There are many fields in which computer vision can be applied (Jain, 1995). Most of them are still academical research, but industrial applications are growing everyday. This section presents a small set of these applications in mobile robotics.

3.1. Welding

Welding processes can be helped by the use of computer vision. Many researches use vision systems to deal with problems that cannot be handled by other sensors. A well known application is the visual servoing to control the position of a welding gun in the pool. A new use of vision in welding is in the field of underwater welding, in that a underwater mobile robot is placed near a submerse pipe and has to weld by means of the camera's images. The later application is up to now in development in some research centers. Figure 4 shows the robot's motion based in vision analysis at GRACO's laboratory.

3.2. Shape Reconstruction and Object Recognition

Shape Reconstruction and Object Recognition are two important Computer Vision areas if one needs to identify and locate objects in a 3-D space. Three-dimensional shapes can be reconstructed from intensity images from stereo, motion, focus/defocus (Chaudhuri, 1999), zoom, contours, texture and shading (Trucco, 1998). Shape from shading and texture do not require special hardware, and do not depend on image pre-processing (unlike for instance shape from contours, which assumes that the contours of objects have been identified). Among all these ways to estimate shape, shape from shading and texture can be reconstructed from just a single intensity image.

Object recognition entails two basic operations, identification and location (Jähne, 1997). Identification determines the nature of the objects imaged. For instance, whether there is a car among many objects in an image, or whether the only object you are looking at is indeed a car. Location determines the position in 3-D space of the objects in view, and needs that the identification problem is a model-based task. A model of the geometric image formation (sensor model) has to be completely known, and object models are based on geometric features. In summary, the three steps of object recognition are:

1. Object identification, which selects object models from a database of models and establishes the correspondence of model and data feature;
2. Model-based location, which positions the selected models in space;
3. Verification, which filters out the hypothesis (located models) that prove inconsistent with the input image.

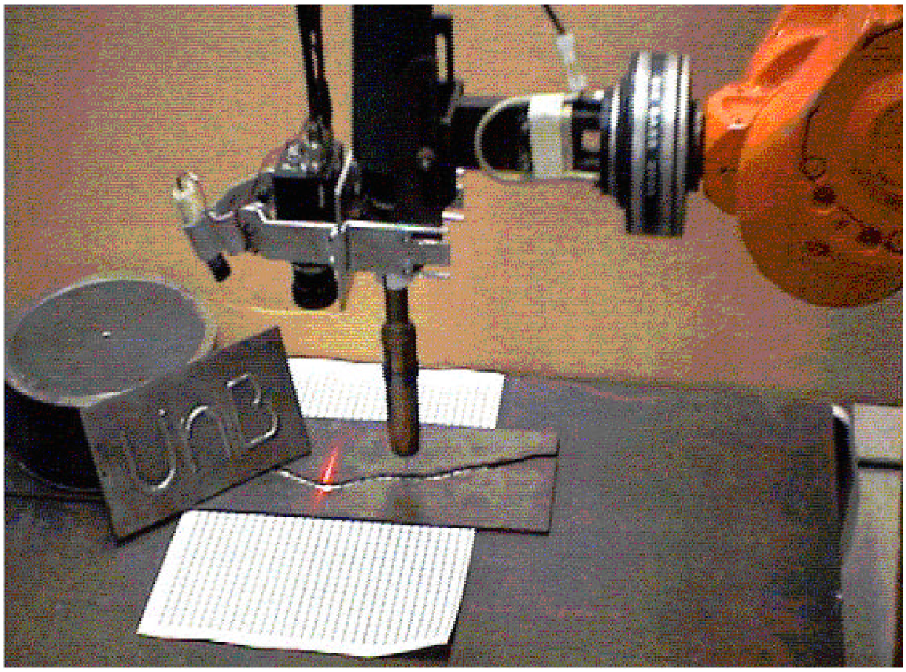

Figure 4. Welding process with vision support.

3.3. Robot Navigation

Simpler approaches in the field of mobile robot's navigation like time-of-flight sensors (sonar) and infrared sensors are mostly used due to their faster implementation. Vision systems are the state-of-art in the navigation technology, but this position has the price of greater complexity and slower development. Since vision is a multiple sensor (can capture a lot of information in one image) its information density is far greater than the other sensors, bringing to the system better knowledgment of its environment at the expense of an increased computation effort. Many researchers are currently working in the field of vision-based navigation over the world (Zelinsky, 1996; Daniilidis, 1998). Figure 5 shows the Xavier mobile robot, that uses vision system to navigate in its environment..

Figure 5. Mobile robot and its visual based navigation.

4. SYSTEM'S ARCHITECTURE

This work is related to mobile robot's navigation by means of computer vision. The system's architecture is based on few modules, in which each module is defined to carry out a small set of operations, improving the overall system's performance and maintenance.

4.1. Image Capture

The image capture module is related with the camera and the framegrabber in the robot's hardware. In this module the frame rate and the image size are the most important parameters that can be set. The framegrabber, a Matrix Meteor card, is able to capture images up to 30 frames/sec (as been stated by the manufacturer). Its performance is good enough to a navigation system.

4.2. Image Pre-Processing

The pre-processing module is responsible for the image's noise reduction, image feature extraction and, in some cases, pattern recognition. This module is based on software written in the C language, where data from the image capture module is transformed to suitable data for the next module (motion detection).

4.3. Motion Detection

The motion detection module has a duty to detect and interpret the motion of the object in focus and/or the robot's motion, generating useful data to the robot's controller. The motion detection can be realized by the optical flow approach (Jain, et al, 1995), in which a sequence of images is analyzed and the pixels' motion is calculated, generating a vectorial picture of the object's and robot's velocity. This approach is also a suitable method to locate objects in vision-based navigation, since either objects or the robot have usually motion related to each other.

The optical flow of an image can be generated by several approaches (Beauchemin, et al, 1995), including differential methods, in which the system gets a dense motion data calculated from the *optical flow constraint equation* (see eq. 1); frequency-based methods, using orientation filters in the Fourier domain of time-varying images and in general using FFT algorithms; and correlation methods, that uses the correlation formulae from statistics to extract the motion information.

$$\nabla I \cdot v + I_t = 0 \quad (1)$$

Where:

∇I Image gradient (I_x,I_y)
v Velocity vector (u,v)
I_t Image's time differential

4.4. Robot's Control

The robot's control module includes the control algorithm that gets the image data as input and creates as output the robot's motion (in the floor plane). This module can be implemented by several approaches, including: neural nets (Lynch, 1999), in which the controller learns the inputs and desired outputs to map a nonlinear response that must be adequate to the designer's wishes; fuzzy logic (Boudihir, 1998; Shaw, 1999), in which a set of variables, pertinence functions and rules are defined by the designer to cope with the system's requirements; and Kalman filtering (Maybeck, 1979; Zelinsky, 1998) , that based in a dynamic model of the system can create an optimal controller.

4.5. Modules of the System

This section presents a simplified sketch of the relationship among the presented modules of the robot's navigation system. The fig. 6 displays the system's modules.

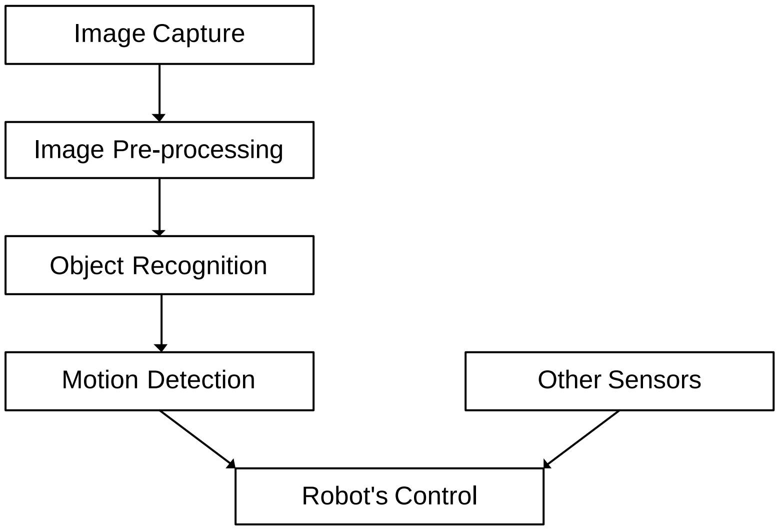

Figure 6. Modules of the visual based navigation system.

5. ALGORITHM DEVELOPMENT

The system algorithm aims to perform the following tasks:

1. Simplification of grayscale images;
2. Object recognition and depth reconstruction;
3. Measurement and 3D positioning of objects (Jung, 1998), based on dynamic scenes and image flow analysis (Liu, 1998).

These requirements are defined to permit the robot to follow an object by means of its vision system, locking the relative position of the object in the image captured. To accomplish this task, the algorithm sequence of development will be guided by the following steps:

1. MatLab simulations

Since the MatLab environment is full of mathematical tools and its language is similar to C, it is a very good platform to test and evaluate algorithms. This part of the work is divided in:

a. Scene creation : development of algorithms that can simulate a real image get from the robot, simplified to speed up the simulations.
b. Image processing : this part is related to all the task in machine vision subject, like pre-processing, object recognition and image flow analysis.
c. Robot control : MatLab can also simulate dynamic control systems with its Simulink environment. Will be defined a simple model of the robot to be simulated under the visual data and in the Simulink platform.

2. Robot Implementation

After all tests the processing image algorithm and robot's controller will be translated to the C language in the robot's system. This part of the work will be simplified due to the similarity of MatLab's language and the C language. It will be used the *Nclient* library, provided by the manufacturer, to control the motion of the robot, and the Meteor's functions to cope with the image capture programming.

6. CONCLUSIONS

This work presented the main steps of a multi-task vision system in development to work with the Nomad XR4000 mobile robot control system. The algorithms are supposed to be fully compatible with the robot control libraries, and in return a high efficient vision-based navigation system can be implemented on the robot's Unix platform. The development of Computer Vision algorithms of segmentation, object recognition, and motion analysis specifically developed for 3-D localization will allow a powerful laboratory robot to test a multitude of new challenging intelligent systems of robot learning vision-based navigation..

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