VISUAL CONTROL OF TELEOPERATED CELLULAR ROBOTS

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ABSTRACT

This paper describes a system for vision-based remote control cellular robots. Cellular robots have numerous applications in space where several units can be used to perform different tasks that involve covering a large working space.

These robots are controlled based on the visual input from one or more cameras that monitor the working area. The control of the robot along a pre-defined trajectory is achieved without depending on the camera calibration information. The remote user simply specifies a trajectory or a target point in the image to indicate the robot mission.

1 INTRODUCTION

The system described in this paper consists on a number of small cellular robots equipped with a radio connection to a local computer. The robots workspace is observed by an external camera. Images provided by this camera are made available to a (possibly remote) user to perceive the robot and surrounding scenario, as shown in Figure 1.

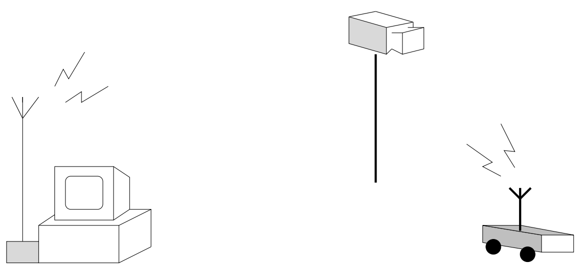

Figure 1: Overall system setup

The goal of the system is to allow the remote user to design trajectories over the image or indicate image points that should be reached by the robot. Then, a vision based controller [3] drives the robot along the desired trajectory or towards the desired goal point.

This framework is quite powerful for two main reasons. Firstly, the user interface is kept at its simplest level: the desired trajectories or goal points for the remote robot to attain are directly specified on the image plane. The user does not need to have any metric knowledge about the robot workspace. The only coordinate system involved in this process is that of the image plane. Secondly, the vision based control loop automates the process of driving the robot along a specified trajectory or towards a given point. Therefore, the remote user is freed from the tedious and difficult operation of keeping the vehicle constantly under teleoperation.

The control system must incorporate the information regarding the camera coordinate system and that of the robot or ground surface. Determining such coordinate transformation can only be done through a time consuming and difficult calibration procedure. In our approach, the overall system is shown to be independent of the camera position/orientation and the user can then operate the system irrespective of the camera position/orientation.

2 UNCALIBRATED VISION BASED CONTROL

The vision based control system is responsible for driving the vehicle according to a user-specified trajectory or goal point. The vehicle is controlled in closed loop based on measurements of its position, velocity and orientation estimated from the observed images.

A fast tracking algorithm, based on an $\alpha - \beta$ filter, is used to estimate the vehicle position and orientation on the image plane. Detailed information can be found in [2].

The vehicle dynamics and kinematics were modeled and a suitable dynamic controller based on linear control theory has been proposed. The controller acts upon the vehicle linear and angular velocities, in order to achieve the control goals, both in trajectory following of point-to-point movements.

It is important to stress that, even if the reference trajectory and the robot motion measurements are all described on the image plane, the vehicle motion commands are nevertheless described in the vehicle (euclidean) coordinate system. This coordinate transformation describes the perspective projection process as well as the camera position and orientation, with respect to a world frame. The image formation introduces a (perspective) non linearity in this mapping. Figure 2 illustrates the non linear transformation between points on a ground plane and the image plane.

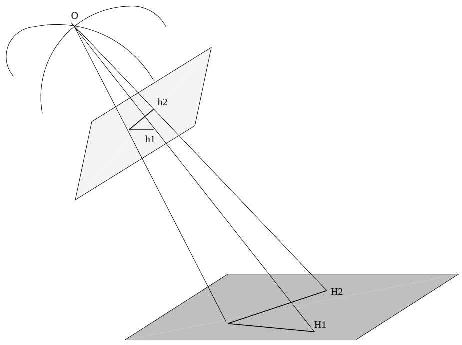

Figure 2: Non linear (perspective) transformation between points on the ground surface and the image plane.

If these world-to-image transformation is known, then all image measurements can be transposed back to the vehicle coordinate system. However this procedure would require calibrating the camera, by specifying the 3D coordinates corresponding to a number of points visible in the image. This is usually a difficult problem, particular in space applications, where a calibration object cannot be easily introduced in the scene. Moreover, if the camera moves, then the calibration process would have to be repeated.

Alternatively, one could try to design the control system without assuming prior knowledge about the world-to-image transformation. This would add much more flexibility to the system, since calibration would no longer be required and the system could be used independently of the specific camera position and orientation. In this case, the overall accuracy of the system would be independent of (or more insensitive to) the errors in camera the calibration. The independence from calibration is very important, since the overall system becomes much more flexible to use and can cope with changes in the camera position/orientation.

In [4], we have shown that a closed-loop control system can be designed in such a way that it remains (locally) stable for any (unknown) camera position/orientation, except when the image plane becomes perpendicular to the ground plane. Hence, this approach can be used in a scenario where the camera is not set in any particular position in the working environment, which is often the case in space applications.

In the analysis done, to demonstrate the overall system stability independently of the camera pose information, we assume that the terrain can be locally modeled as a planar surface. However, the system can work in situations where the ground is not necessarily planar and hence, it may have a wide spectrum of applications in the domain of space robotics.

3 EXAMPLE EXPERIMENT

This approach has been tested by using several cellular robots equipped with RF communication with a computer. One of such vehicles is shown in Figure 3. Each robot has a different address and the a single computer can control various robots performing different tasks or cooperating for a more complex task, as for transportation of large objects.

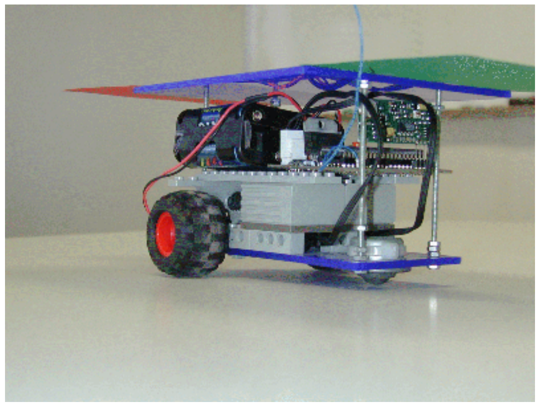

Figure 3: Radio controlled robot used for the experiments.

Currently, the system runs at video rate (25Hz) using a standard PC with a Pentium processor without any special processing hardware. As a consequence of the use of vision based control from an external camera, we can keep each robot quite simple in terms of hardware. There are no additional sensors installed onboard. Feedback is provided exclusively through the vision system. As such, building a large number of such vehicles is not prohibitive in terms of cost.

Experiments were carried out to drive to robot towards a goal position. The camera is positioned so as to cover the robot workspace and no calibration was performed. The camera orientation/position was modified between different experiments. Figure 4 shows two examples of a trajectory performed by the vehicle in the modes of *go-to-point* and *trajectory following*.

Notice that the user intervention is limited to the specification of an image point or trajectory to indicate the mission to perform. There is no need for specifying any three-dimensional coordinates in the robot workspace. Mission specification becomes a very natural task for the remote user.

Finally, in Figure 5 we show simple examples of cooperation between the vision based controlled cellular robots. In the first example, two robots are con-

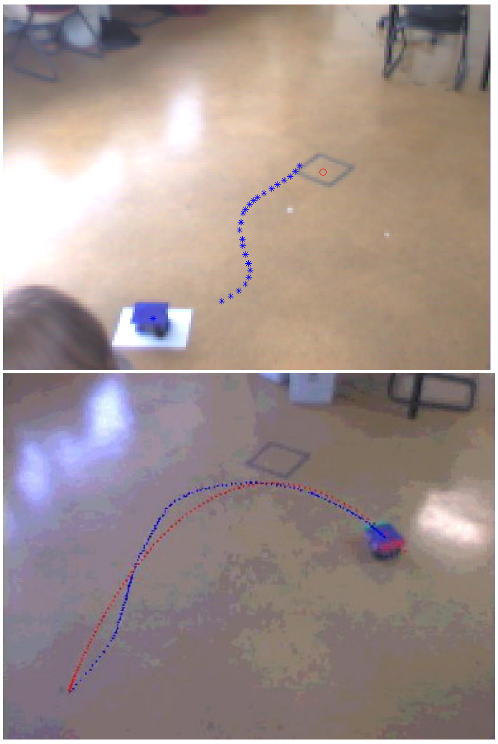

Figure 4: Trajectory executed by the cellular robot under vision based control. Top: example of going towards a final point. Bottom: trajectory following.

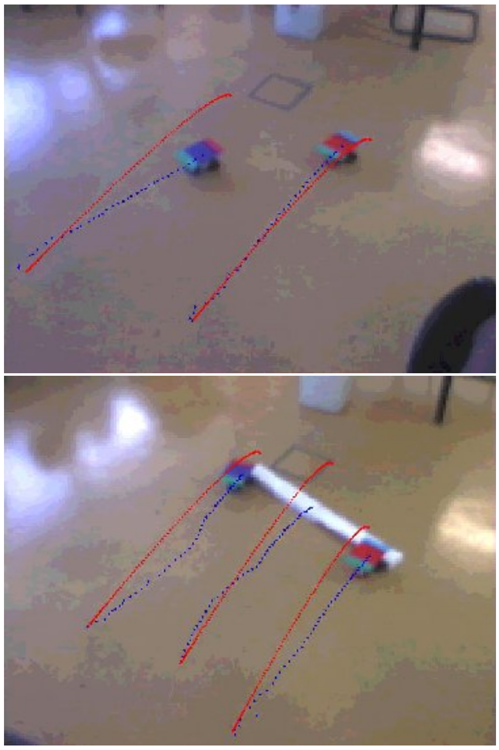

Figure 5: Examples of cooperation between multiple robots. Top: maintaining the relative orientation (formation control). Bottom: two robots pushing an object (bar).

trolled to maintain their relative orientation and in the second example two cellular robots cooperate for pushing an object (white bar) to a desired configuration.

4 CONCLUSIONS

We have described the principles of a visual based control system for the teleoperation of cellular robots. In space applications, this approach can be used for the remote control of planetary or exploratory rovers with two main advantages. First, the user can specify missions in terms of trajectories or points to reach, simply by drawing on an image of the robot workspace, thus avoiding the need to know 3D coordinates of the vehicle's environment. Secondly, the system is stable independently of the camera position and orientation in space. It does not depend on calibration data and therefore does not require any recalibration if, for instance, the camera position is changed

The additional flexibility arising from the independence of the camera calibration is of the utmost importance, since it relaxes the requirement of precisely placing the camera in a pre-specified pose or performing extensive system calibration experiments. Naturally, the control performance depends on the camera position and can degrade significantly for extreme changes in the camera orientation (e.g close to singularities). The problem of addressing the optimal (adaptive) control parameters for any camera position and orientation is being considered for future work.

One interesting extension is the use of multiple cameras observing a large environment, or a moving camera. From a theoretical point of view this is exactly the same problem as the one we described. If the cameras projection matrices are estimated, then we can relate pixels of the various images, simply by composing the various projective planar transformations mapping between pairs of images.

Alternatively, we may prefer to keep the system uncalibrated feature of the system, as the control system does not depend on the information about the cameras geometry. In this case, it would not be necessary to explicitly relate the coordinate systems of the various images, as the control could be easily switched between the various cameras. If both the robot and the goal are visible in more than one camera, one could use the multiple angular errors in the global robot controller, thus explicitly benefiting from the existence of multiple measurements to further improve the accuracy.

This system is part of a more general framework of using visual information for the closed loop control of robotic systems with different geometries [5, 1, 6]. A common characteristic is that by using visual information in closed loop, the overall system becomes much more insensitive to uncertainty in some of the system parameters and, as in the example discussed in this paper, the need for calibration may be completely avoided. We believe that this aspect is of crucial importance in space applications where calibration objects are not usually available.

5 REFERENCES

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