OBSTACLE AVOIDANCE FOR TELEOPERATED ROBOTS FOR LIVE POWER LINES MAINTENANCE, USING ARTIFICIAL VISION.

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Abstract: Nowadays uninterrupted power supply has become a must for electrical companies, due to the increasing technological advances, present in our society, that lead to higher demands of electricity. This strong need is obliging the electrical companies to develop processes and techniques for outage-free maintenance of electrical power supply, whose major application lies in aerial distribution lines. In these conventional techniques workers have to do their job on a live electrical power line indirectly, with various kinds of hot-sticks or directly touching the line with rubber-insulated gloves. Therefore, work is performed in a hazardous environment with both, the risk of electric shock and the danger of falling from a high place. In addition, workers have to be very skilled and work cooperatively under very demanding tasks. For all these reasons, the European Community foresees the suppression of this operation in a short term. This paper presents a teleoperated system, developed at DISAM*, capable of performing electrical power lines maintenance and inspection, tasks. The general features of the project are explained, paying special attention to the artificial vision system, which is an obstacle avoidance system capable of preventing collisions between robots and the electric cable. Such a system is the result of several years of research on computer vision.

Keywords: Obstacle Avoidance, Teleoperation, Artificial Vision, Stereo Vision, Calibration, Path Planning.

1. INTRODUCTION.

This work has been developed at the Departamento de Ingeniería de Sistemas y Automática (DISAM*), which belongs to the Escuela Técnica Superior de Ingenieros Industriales (ETSIIM) at the Universidad Politécnica de Madrid (UPM).

The system consists of two hydraulic driven manipulators with six degrees of freedom, placed on a rotating platform on top of an insulated boom, which substitute the workers in performing the hazardous work on the hot line. The operator, instead, is located on the ground, from where he teleoperates the slave manipulators via two force-reflecting masters arm. Since many maintenance operations may be performed automatically, both, the safety of the workers and the overall efficiency of the task are increased. In the other hand, this system includes a vision module, which consists of two different subsystems:

Visual inspection system for the operator. Due to the fact that the operator does not have a clear view of the operation that is being performed, two cameras have been installed to help him supervise his work. The first camera is attached to the left manipulator and allows the operator to visualise the operations performed by the other manipulator. The other camera includes a motorised lens with zoom, focus and iris control and it is set on a pan-tilt unit on top of the system. This

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camera provides a panoramic view of the working area to the operator, and therefore, a feeling of being performing the job directly. Since the operator has both arms engaged, he can command this camera by means of a multimedia interface with voice synthesis and recognition.

Collision detection system. It basically consists of a binocular stereo mount and a laser illuminating system. This system is responsible for avoiding collisions between the manipulators and the lines that would lead to a short-circuit situation. The main problems related to the use of a vision system are found in the need for reducing the noise introduced by sun's light and the quick detection of the position of the cable. This issue is of special importance, as the true spatial position of the cables must be known to avoid any action, whether deliberate or unintentional, that may cause a disaster.

The system may be considered as semiautomatic with the operator on the ground. In a first stage, a supervisory control in some degree has been implemented, although the final objective is to reach supervisory control next to fully automatic control. Some advantages of this way of operating, in contrast to a manual operation, are a higher level of protection, safety for the worker and quickness. As disadvantages, may be considered those related to the higher complexity and cost.

2. SYSTEM DESCRIPTION AND ARCHITECTURE

2.1. General structure

The system has been designed to develop maintenance and repairing tasks on overhead distribution lines of up to 49 kv. Table 1 briefly describes its principal elements. The architecture is oriented to allow the operator to perform tasks in an optimal manner and in the fewest time, and to achieve the highest degree in telepresence and therefore, increasing the performance of the system.

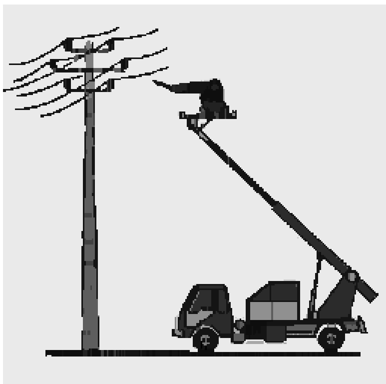

Fig 1: System set up.

Table 1: Main system components.

Truck	5.5 ton, 8 m long
Boom	15 m long, telescopic and with up to 69 kV of dielectric strength.
Cabin	Mounted on truck chassis, next to truck cabin. Includes the operator post with the boom, jib and manipulation control stations
Robots	Hydraulic; 7-function (6 axes + grip); articulated. Masters with force feedback; max. Payload 45 kg/arm; net weight 60 kg/arm
Jib	Hydraulic; 3 dof ; telescopic; lifting capacity: 200 kg; with winch
Rotating platform	Mounted on top of the boom. Holds the slave manipulators, the jib and the vision system
Vision System	Stereo head, laser scanner, and real time frame grabber.

The system consist of three different modules: HIC, (Human Interactive Computer), TIC (Task Interactive Computer), SPC (Sensor Processing Computer).

The HIC is responsible for the interaction of the system with the operator, so that the control loop of the system is closed. The TIC receives commands from the HIC and takes the proper actions on the manipulators and other controlled devices. Finally, the SPC processes the information that the remote sensors provide. A more detailed information in (Santamaría, *et al.*, 1996; Aracil, *et al.*, 1995,).

Communication between the different modules is performed via ethernet, whereas the exchange established between the TIC and SPC is made on a VME bus.

2.2 Structure of the vision system.

In this section, the different elements that constitute the SPC system are described in detail.

TRC motorized lenses stereo mount. It is a binocular stereo head developed by the American Company TRC (HelMate Robotics Inc., at present). It is controlled by an 8-axis PMAC controlling card set on a VME bus. The head has four degrees of freedom, that is: pan, tilt and vergence on each camera. Besides this, both cameras include motorized lenses with three degrees of freedom: zoom, focus and iris.

Datacube Maxvideo 200 video processing board. It is a real time acquisition and image processing VME board with a pipeline architecture. It is mounted on a

VME chassis with a Motorola 68.000 as a host, running Lynx 2.0 Operative System.

Floating point processor Max860. It is a high performance floating point RISC processor that complements the existing real-time Datacube hardware by providing speed and flexibility for implementing virtually any image-processing algorithms. It allows general purpose floating point operations, processing data at 40 MHz for a peak performance of 160 Mflops. It may be programmed using an i860 cross-compiler, assembler and linker and includes different libraries for controlling data transfers, inter-processor communication and event management. This processor, together with the Maxvideo 200 processing card and the host processor, make up the SPC.

810 nm laser scanner. This equipment has been developed at the Universidad Carlos III de Madrid and consists of a 500 mW semiconductor laser and a cylindrical lens that generate a vertical laser beam. This beam may be oriented by means of a mirror attached to a galvanometer. The engine that positions the laser beam is controlled through the host serial port. Besides, it allows a sweeping operation in which the maximum and minimum sweeping range may be selected. The laser switching on and off may be performed automatically or synchronized with the integration frequency of the cameras.

It is worth mentioning that radiation safety of laser products equipment rules, UNE (Aenor, 1993) have been taken into account to ensure a safe use of the system.

3. DEVELOPMENT OF THE PROJECT.

3.1. Technological problems and solutions presented.

The main problem of detecting a cable is that there is not any significant point of the cable available to solve a typical correspondence problem. In a laboratory, under controlled illumination conditions (as shown in figure 3), it is possible to calibrate the stereo unit with accuracy and to perform a segmentation operation on the cable in order to obtain its spatial position. Nevertheless, when attempting to perform the same set of operations under sun's light, being the stereo mount on top of a boom over a truck, the results obtained may not be as good as expected. Another factor to take into account is the fact that the cable is approximately parallel to the epipolar line, so that any lack of precision may cause very large errors.

In order to solve the first problem, one may make use of active vision resources, such as illuminating

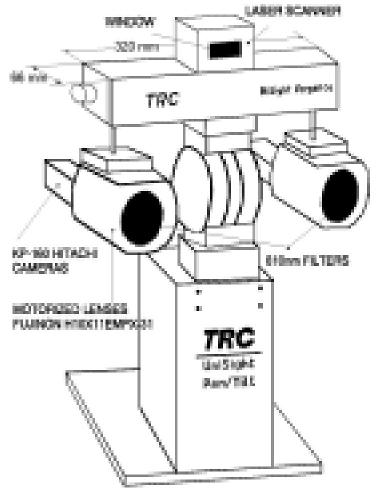

Fig 2: Stereo head mount.

the cable with a vertical laser beam so that the intersection may be within the field of view of both cameras. Thereafter, this point of intersection may be detected in both images and the problem of correspondence may be solved. If is possible to obtain a set of 3D points that belong to different portions of the cable, it is easy to create, by means of interpolating, a security area around the true position of the cable. This way, the manipulator will not be allowed to cut across this area and touch the cable.

The next problem to be solved is the amount of noise that sun's light involves. The working conditions of the system are very often subjected to a strong solar illumination, a very common situation in our country. The system though, should be able to work against the light. This fact implies that the employment of structured light in this environment may be useless.

The solution to overcome this second problem involves acting on the power and wavelength of the artificial light supply. The sun, even though it behaves as a black body, stands a fall in energy density in the infrared range, being this descent larger as the wavelength increases.

The problem of selecting a larger working wavelength is that the cost of both, cameras and laser equipment, increases radically. Furthermore, for wavelengths higher than 900 nm there are not any commercial CCD cameras and solid state lasers available nowadays. As a result, it would be necessary to consider other technologies, which besides the higher cost may occupy an excessive volume, making this solution non-viable.

Finally, the solution selected consist in a 810 nm laser with an output power of 200 mW and two Hitachi KP-160 cameras, each one provided with a 810 nm filter of ±10 nm passing band. By means of this equipment, we are able to visualize and detect the intersection of the laser with the cable very sharply, even under strong solar illumination conditions.

3.2 Functioning of the vision system.

When the platform approaches the cable, the system starts being able to detect the location of the line. As soon as the cable is spatially positioned, its 3D coordinates are added to the database, which stores the wired model of the scene in front of it. Whenever the operator commands a movement on the manipulator, the system checks if the trajectory is compatible with the model and that no collision is possible. The operator may enable or disable certain space areas in order to prevent the manipulator from crossing them accidentally. The worker performs this operation using a voice driven interface, since he has both arms engaged in controlling the master arms.

The laser is turned on and off synchronously with the camera in such a way that, it is on during the even frames and off during the odd frames. This way, the Datacube unit may process two images and detect the differences between them. The illuminated spot is detected in both images, corresponding to the left and right cameras, and the coordinates are then passed to the max860 equipment, which solves the correspondence problem.

Two different detection strategies have been implemented. In the first place the area of the cable is swept around. This is followed by a more selective sweeping on the area within the field of view of both cameras.

4. ALGORITHM FOR COLLISION DETECTION

This chapter explains in detail the basis of the vision algorithm. The analysis is divided into different stages.

4.1 Strategy of image acquisition

Two different detection strategies have been implemented in the system, as was pointed out in the previous section. According to this, the system always follows the first strategy in the first place. Once the position of the cable has been correctly detected, the second strategy plays its role. If there is a chance that the collision detection algorithm is failing, an alarm message will be displayed on the operator screen indicating that the operations are not completely safe and that every precaution must be carried into extremes.

First strategy. The stereo head moves steadily form left to right sweeping the cable area around horizontally. The intersection of the laser beam with the cable remains inside the field of view of both cameras at every instant of time. The cameras

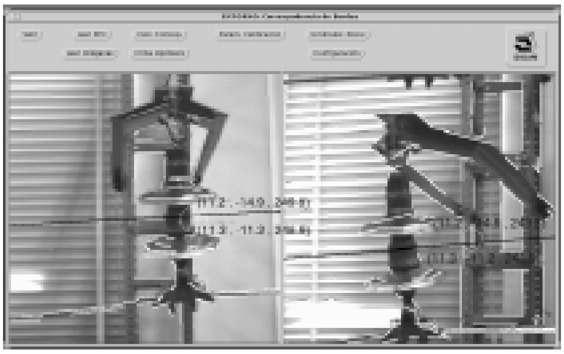

Fig 3**:** Image correspondences made at the laboratory

are fixed at a constant position with respect to the eyes coordinate system although they present a small vergence angle. During this motion, the vision system will be identifying points that belong to the cable. The spatial position of these points is calculated in real time by the algorithm explained in this section.

Second strategy. The mount remains still while the vertical laser beam is sweeping the cable around within the cameras field of view. Just like in the previous case, the points are calculated in real time and the point coordinates are added to the TIC database.

4.2. Calibration of the vision system

The calibration of any vision system is crucial in order to obtain a degree of accuracy. In the case of this binocular stereo mount with motorized lenses, a calibration table has been calculated for a wide range of values of the zoom and focus.

Due to the fact that the working distance is approximately constant, being this distance limited by the length of the manipulators, the cameras are thus set almost at a constant distance with respect to the cable. Thereby, it is only necessary to make certain adjustments on the focus by means of an automatic focusing system, (Jiménez, 1995b). Since the stereo mount is rotating horizontally from left to right, it is necessary to perform a kinematic calibration (González, 1996). In the following paragraph, the method employed for the kinematic and camera calibration is analyzed.

Methods: Calibration of motorized lenses involves a higher complexity than that of a fixed lens. It can be considered that a lens behaves according to the mathematical pinhole model for a set of specific zoom, focus and iris values. Nevertheless, once any of these values is modified, the intrinsic and extrinsic parameters of the method are affected, mainly because of the displacement that the center of the image suffers. (Gonzalez, 1996; Wilson, 1994). The mathematical model employed is the well-known pinhole model which is explained in detail in a vast number of publications (Tsai, 1989; Li and Lavest, 1994; Wilson, 1994; Gonzalez, 1994).

Intrinsic parameters. The projection of a point P on the CCD plane comply with equation (1) in which (x_w, y_w, z_w) are the coordinates of P with respect to the world coordinate system. (x_f, y_f) represent the coordinates of a point in the image measured in pixels. The rotation matrix [R] defines the spatial transformation of the coordinate system, being its 9 parameters a function of the angles rotated. The other 3 parameters of the translation matrix [T] correspond to the displacement of the origin of the coordinate system from the optical center. The parameter f represents the focal length of the camera. D_x and D_y represent the tangential and radial distortions in each direction. In order to change from coordinates in millimeters to coordinates in pixels, It is necessary to multiply such values by a scale factor K_x and K_y and thereafter, also to displace the principal point C_x, C_y

$$X_f = C_x - K_x D_x + K_x f \frac{r_{11}x_w + r_{12}y_w + r_{13}z_w + t_x}{r_{31}x_w + r_{32}y_w + r_{33}z_w + t_z} \quad (1)$$
$$Y_f = C_y - K_y D_y + K_y f \frac{r_{21}x_w + r_{22}y_w + r_{23}z_w + t_y}{r_{31}x_w + r_{32}y_w + r_{33}z_w + t_z}$$

Finally, the coordinates of the image or frame can be expressed in terms of the intrinsic and extrinsic parameters of the system (1). These are referred to by photogrammetrists *as collinearity equations*.

Calibration process. Several algorithms have been tested in order to obtain the intrinsic and extrinsic parameters. Among them, some deserve special attention: Tsai's method (Tsai, 1987), DLT method (Fan and Yuan, 1993) and Vanishing Point method (Wang and Tsai, 1991). The algorithm that finally has been employed in the system is Tsai's method, both Reg Willson's (Carnegie Mellow University) and Janne Heikkiläs (Heikkilä and Silven, 1996) (University of Oulu, Finland) implementations. In both cases, the results obtained are much better than when other methods are used.

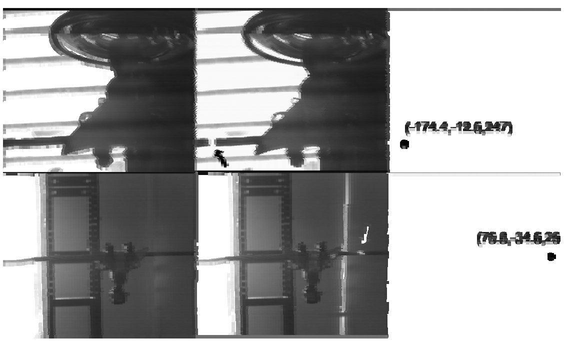

Fig 4: Example of cable coordinates detection

Kinematic calibration. In any active vision system, the intrinsic and extrinsic parameters change when the position or the camera state vary. Therefore, it is necessary to develop certain calibration techniques such that may maintain the system calibrated under any conditions. The intrinsic parameters will be modified according to the position of the stereo mount. That is, whenever the tilt, vergence or pan values change, the system will read the new parameters from a set of tables (Tsai,1987). Other authors propose the development of mathematical formulas such that the intrinsic parameters may be obtained in terms of the position of the zoom, focus and iris (Wilson, 1994).

The problem of continuously knowing the values of the extrinsic parameters can be solved by means of a previous calculation of a set of transformation matrixes. Such matrixes relate the camera coordinate system, located at the center of projection of the image, and the coordinate system that defines the axis of rotation of the stereo mount.

By knowing the extrinsic parameters at an initial position in which we have calibrated the system, and by obtaining previously every transformation relationship between the different coordinate systems, it is possible to calculate the extrinsic parameters of the camera at any time. (Li *et al.*, 1994)

4.3. Description and on-line implementation of the algorithm

The process of acquiring and processing the images taken by both cameras may be summarised in the following steps: first an acquisition of both images, being the laser turned off. Second a filtering and noise reduction of every image. Third a subtraction of the laser-on-image minus the laser-off-image in each camera. Forth a binarization on each result images. Fifth, Morphological operations to eliminate false responses. Sixth a detection of possible points and their coordinates. Seventh shape analysis and suppression of false hypothesis. Eighth stereo correspondence. Ninth 3D coordinate calculations according to the intrinsic and extrinsic calibration Tenth, update of the spatial coordinates points database

Steps 1 through 8 are performed in real time by the image acquisition and processing board Datacube Maxvideo 200. This board is a part of the SPC, as was previously mentioned.

Once the cable position has been detected in both images, both coordinates in pixels are passed to a Datacube Max860 processor, which stores the calibration parameters and the position of the stereo mount. Finally, if the operation has been successful, the 3D coordinates of the point are transferred from the SPC to the TIC via ethernet, and the obstacles database is updated. In step 9, the correspondence between two candidate points or primitives takes into account the epipolar constraints and the continuity of each figure (Jiménez, 1995a). On the other hand, in step 10, a real epipolar geometry of the system is developed in order to minimize the mean quadratic error of the false intersections between the projective lines that link the focal center and the primitives of the images.

5. RESULTS

The set of tests that were carried out at the laboratory was completed satisfactorily. It has been possible to measure accurately the localization error introduced by the motion of the stereo mount.

In this case, the manipulators were fixed on a table at a constant distance of the cable and, therefore, the cable spatial position was easily estimated. The only factor that may influence for the correct localization of the cable was the movement of the stereo mount. This error has always been lower than 1 cm., which makes the system accurate enough to work in the field. If we consider the fact that the cable and the platform on which the manipulators and stereo unit are set are going to be swinging, a cylindrical security area of about 30-mm of diameter will be created around the cable. In this way, the manipulators will not be able to cut across this security area.

At present, the system has being tested in the field with a total success. The vibrations introduced to the whole system, by the movements of the robots, and the swing of the platform is corrected by the vision system. The shake added to the stereo mount has been minimized by a shock absorber system. The total collition-free operation has been completely achieved.

6. CONCLUSIONS

The system presented constitutes an important contribution to solve a real problem, as it is the maintenance of electrical power lines. It provides a great amount of information to the operator in order to help him in maintenance and repairing tasks without the risk of an accident. The main technical difficulties encountered during the development of this project are those inherent to any 3D vision system (lack of precision, correspondence problem...), together with the aggressive environment (sun’s light) in which the system must operate.

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