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Teleoperator-Aided Multi-Sensor Data Fusion For Mobile Robot Navigation

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Abstract - This paper discusses a "teleoperator-aided sensor fusion" concept based on an interactive telepresence interface which allows the teleoperator to actually be involved in the world model building.

I. INTRODUCTION

Teleautonomous mobile robots are currently developed for planetary applications, for work in deep sea or harsh terrestrial operating environments, [1] and [2]. Many of these applications are difficult or impossible to automate and robots must rely on remote human operator expertise to carry out navigation and manipulation tasks which require a higher level of intelligence. A proper control of these remote operations cannot be accomplished without some telepresence capability which allows the human teleoperator to experience the feeling that he/she is in the remote environment in which the robot operates, [3] and [4].

Teleautonomy goes beyond the simple teleoperator control in which the robot merely follows commands from an operator who maintains visual contact with the robot. The teleoperator receives feedback data from multiple sensors and issues appropriate control commands which may have different levels of complexity. Usually teleautonomous systems have a shared control architecture in which the human teleoperator performs higher level control functions (above position servoing) which require more intelligence. An onboard computer systems provides as much as possible autonomy for local obstacle avoidance and safety reflex behavior, [1] and [5].

A mobile robot is currently being developed as an experimental platform to study multi-sensor systems for teleautonomous navigation in unstructured environments. Sensory data gathered from vision, infrared (IR) range finders and wheel/joint encoders are integrated in a unique framework which allows one to deal in a common way with the problems of position estimation, obstacle detection and avoidance, and environment map construction. The multi-sensor data fusion system has a hierarchical architecture based on the NASA/NBS standard reference model (NASREM) for telerobot control, [6]. This architecture has an ascending "sensory processing" path in parallel with a descending "task-decomposition" control path connected via "world models" at each level. The amount of processing time at each level is reduced by the use of *a priori* knowledge from the world model that provides predictions to the sensory system. The use of a world model promotes modularity because the specific information requirements of the sensory and control hierarchies are decoupled.

This paper discusses development aspects of a "teleoperator-aided sensor fusion" concept based on an interactive telepresence interface which not only provides the usual visual virtual reality feedback, but also allows the teleoperator to actually be involved in the world model building.

II. ENVIRONMENT MAPPING USING INFRARED RANGE SENSORS

The mobile robot has eight auto-focus IR sensors arranged such to provide a 90° field of view in front of the vehicle. Each sensor has a field view of 6°, along with a measure of the range of a target (up to about 3 m) with medium to high accuracy, irrespective of target reflectivity, [7].

The IR sensor data obtained from multiple points of view are integrated in a unique map of the environment using the *occupancy grid* framework, [8], [9] and [10]. It uses probability distributions that can be described by piecewise-constant p.d.f. The occupancy grid representation, employs a 2-D space tessellation into cells. Each cell of the 2-D grid is characterized by a probabilistic estimate of its occupancy state *P[s(C)=occup]* which can be iteratively updated using Bayes' theorem. The posterior (at the time *t+1*) occupancy probability of the cell C_i, after the new sensor reading r_{t+1}, is given by:

$$P[s(C_i)=occup|\{r\}_{t+1}] = \\ p[r_{t+1}|s(C_i)=occup]\cdot P[s(C_i)=occup|\{r\}_t] \, / \\ \Big(\sum_{s(Ci)} p[r_{t+1}|s(C_i)]\cdot P[s(C_i)=|\{r\}_t]\Big)$$

where $P[s(C_i)=occup|\{r\}_t]$ probability is obtained from the prior state of the occupancy grid and $p[r_{t+1}|s(C_i)$ distribution is derived from the probabilistic sensor model defined as the

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conditional probability density function $p(r|d)$ relating the sensor reading r to the actual distance d, [10].

Sensor view maps taken from different locations of the robot are fused into a global map of the environment. This fusion is done using dead reckoning information (from the vehicle's steering and wheel encoders) to registrate the sensor view maps. A 2-D correlation of the sensor maps containing views of the same landmarks reduces the registration errors inherent in dead reckoning position estimations. Fig. 1 shows the resulting global probability occupancy grid for the a room having the layout given in Fig. 2. This occupancy grid has been segmented by a 60% threshold yielding a binary image. The Modified Adaptive Hough Transform, [11], is then used to extract the boundary lines of the explored room.

III. INTERACTIVE WORLD MODEL BUILDING

The mobile robot navigation control is based on the *shared control* concept, [1], [5] and [12], in which the human teleoperator using (virtual reality) visual feedback is enclosed in the high level and low band-width control loop. A "teleoperator-aided sensor fusion" feature has also been incorporated to investigate the use of the (superior) human image analysis skills to interactively generate world models for mobile robot navigation. The resulting control architecture, shown in Fig. 3, has the peculiarity of having the onboard world model partially generated by the teleoperator.

In the proposed "teleoperator-aided sensor fusion" concept the teleoperator "manually" integrates raster images received from the onboard auto-focus camera equipped with a IR range finder. The range information which accompanies each image and the robot's position sensors provide a certain degree of POSE indexing for these images. This information helps the teleoperator to combine local snapshots in a composite image of the environment as seen from a given vantage-point of the robot. This raster image fusion process is illustrated in Fig. 4 showing four snapshots which were integrated to produce a composite image of the environment from the vantage-point called "A." Similarly, Fig. 5 shows two snapshots which were integrated to produce a composite image of the environment from the vantage-point called "B."

Following a raster-image/graphic-map principle similar with that discussed in [13] , the teleoperator uses computer graphics functions provided by the interactive visual display unit to generates a wire-frame sketch of the visualized objects by drawing lines over the object features of interest apparent in the composite raster image. Fig. 6 shows the resulting wire-frame sketches obtained from the two composite images from Fig. 4 and Fig. 5.

The teleoperator then identifies common vertices in the wire-frame models. This identification provides a *de facto* connection of all vertices thought to belong to the same object. It results into a 2-D partial wire-frame model of that object. The lengths of all vertex-limited segments are automatically calculated by the computer graphic environment from their relative positions in the 2-D image and the POSE parameters of that image.

Based on his/her interpretation of the composite raster images of an object seen from different vantage-points, the teleoperator assigns (Fig. 7) the ground based vertices of the wire-frame models to specific locations on the displayed 2-D occupancy grid of the environment. This assignment/mapping gives the 3-D position at least for the wire-frame model vertices laying on the ground. The 3-D position of the above-ground vertices is then inferred, as illustrated in Fig. 8, by the teleoperator from the specific shape of the polygons seen from different point of views, [14].

The resulting 3-D wire-frame model is ready to be used as virtual reality feedback for the telecontrol of the mobile robot. It is also sent to the on-board computer to be used for autonomous navigation.

The interactive virtual reality display allows the teleoperator to choose between the purely geometric 3-D model of an object and the raster image of that object, as shown in Fig. 9. The teleoperator has also the possibility to inquire about the position of any object on the displayed occupancy grid, as illustrated in Fig. 10. The teleoperator can change these parameters, which will result in an instant modification of the world model.

IV. CONCLUSIONS

Tests of the proposed "teleoperator-aided sensor fusion" technique were limited for the present time to teleoperator controlled navigation functions. Early experiments have proved the validity of this concept from a teleoperator perspective and several interactive graphical user interface modifications were already incorporated in the developed software. Further experiments should test its applicability for autonomous navigation functions.

ACKNOWLEDGMENT

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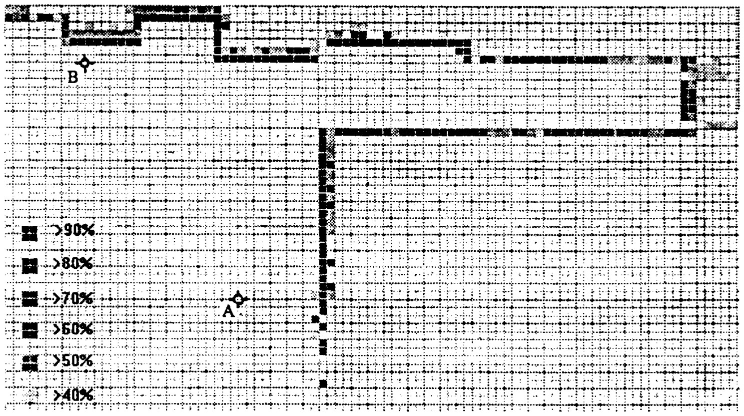


Fig. 1. Probability occupancy grid obtained by multi-sensor fusion of IR range data and robot position data.

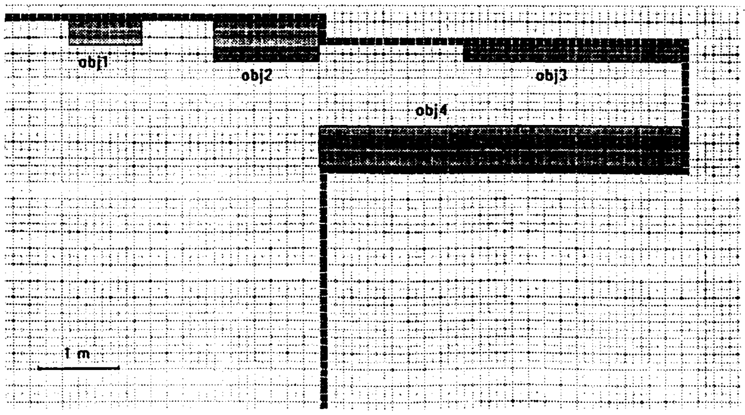


Fig. 2. Actual layout of the room in which the probability occupancy grid of Fig. 1 has been generated.

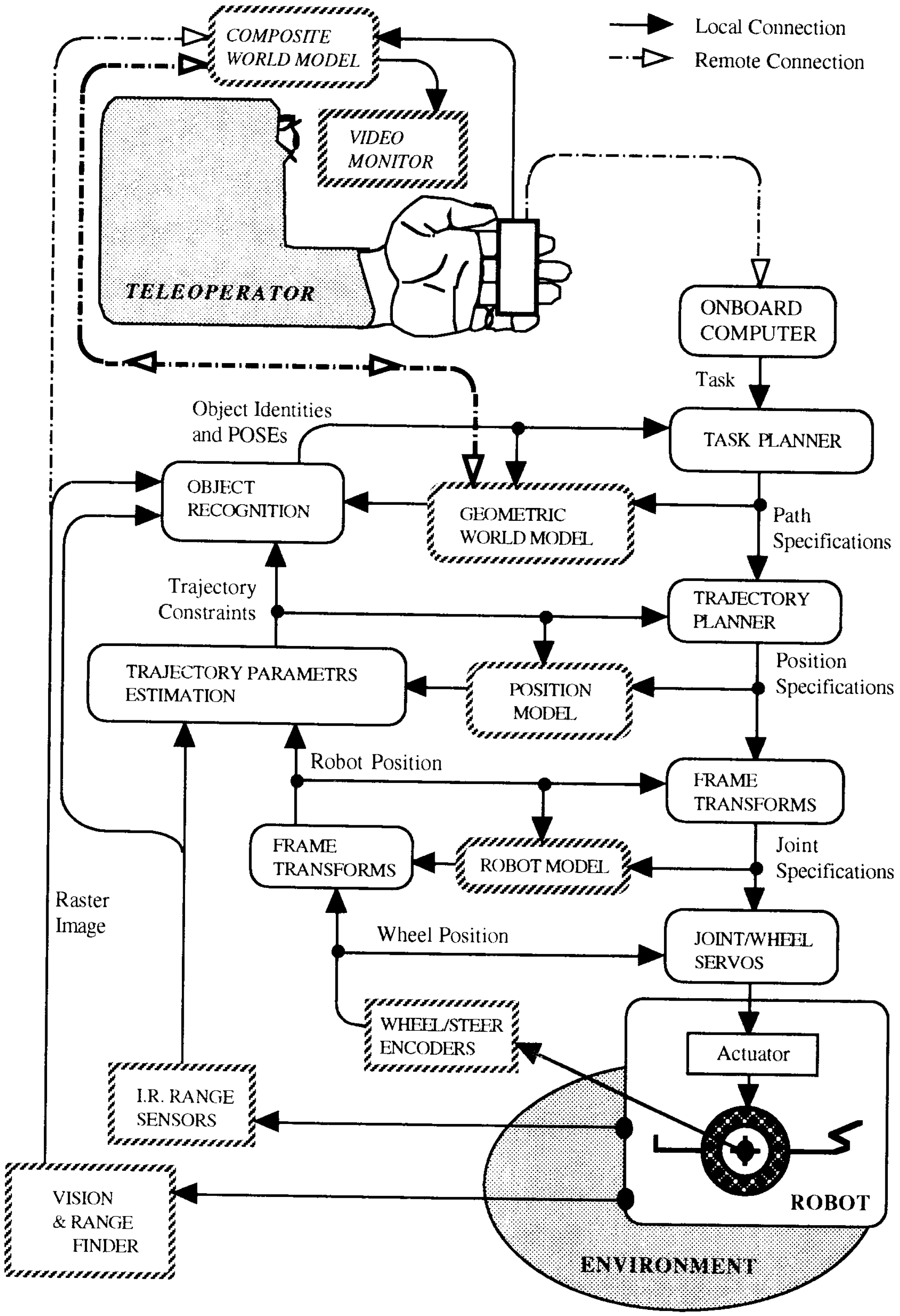


Fig. 3. The multi-sensor system's architecture

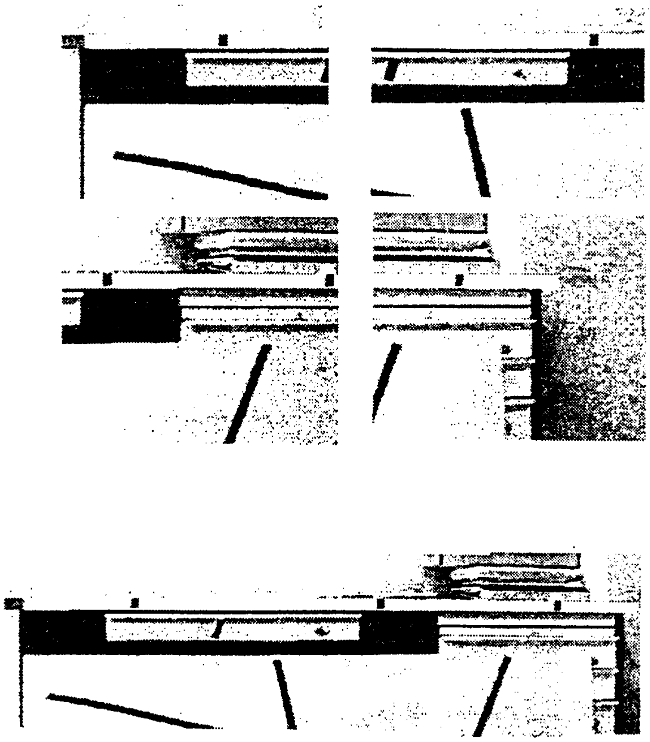


Fig. 4. Partially overlapping snapshots taken from the vantage point "A" (see Fig. 1) and the composite image obtained by their "teleoperator-aided" fusion .

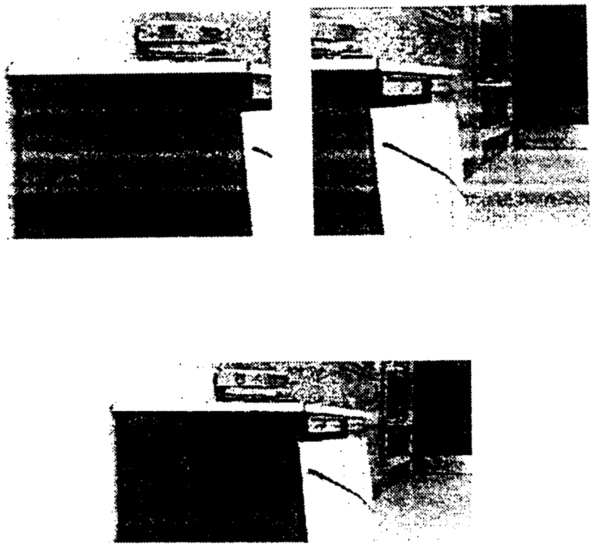


Fig. 5. Partially overlapping snapshots taken from the vantage point "B" (see Fig. 1) and the composite image obtained by their "teleoperator-aided" fusion.

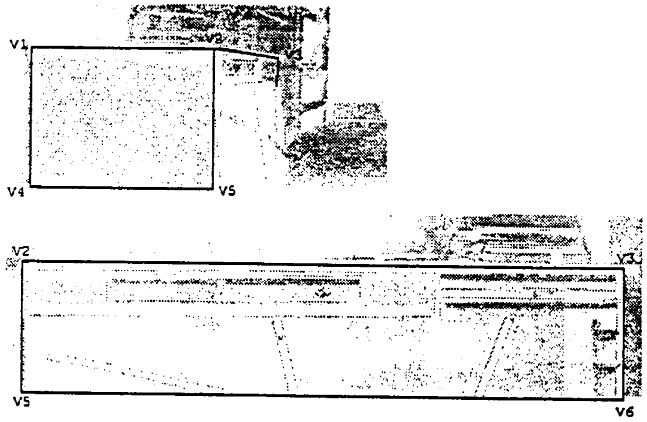


Fig. 6. Teleoperator generated wire frame sketch of objects deemed of interest in Fig. 4 and respectively in Fig. 5.

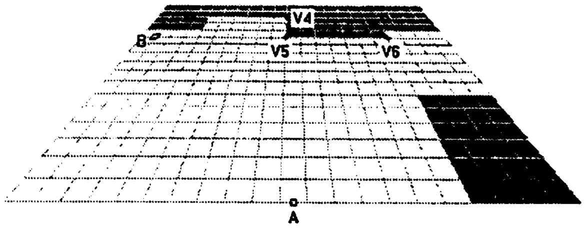


Fig. 7. The teleoperator assigns wire-frame model vertices to specific locations on the 2-D occupancy grid.

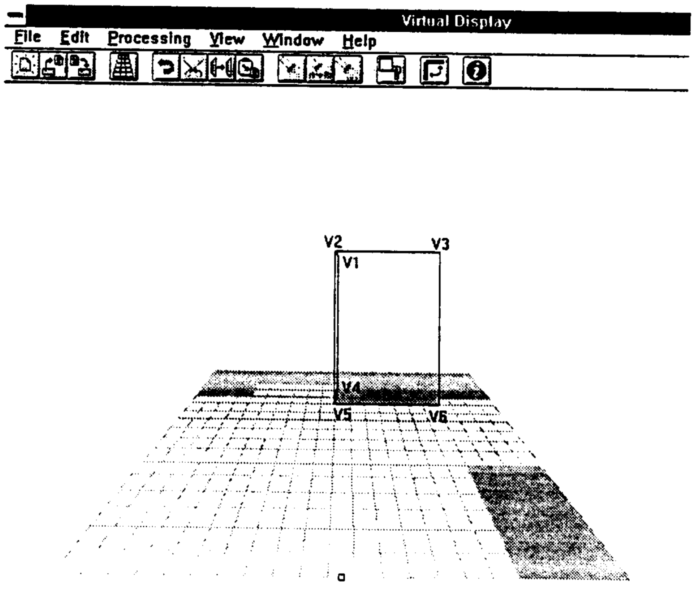


Fig. 8. Resulting 3-D vertex positions for the wire-frame model previously placed on the occupancy grid.

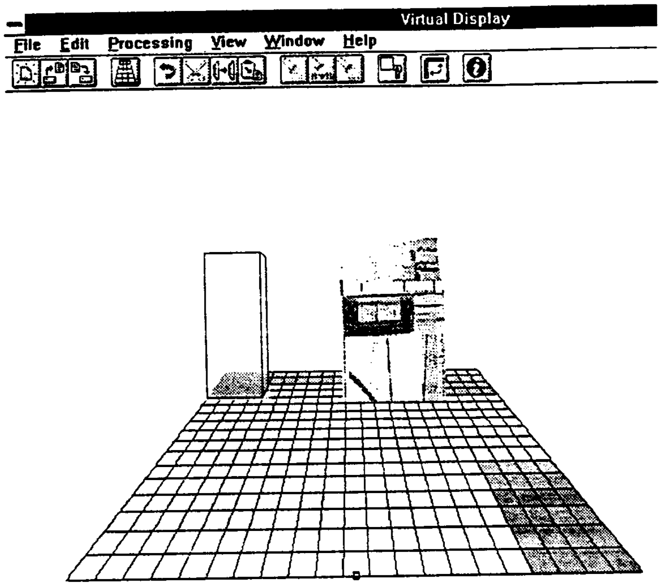
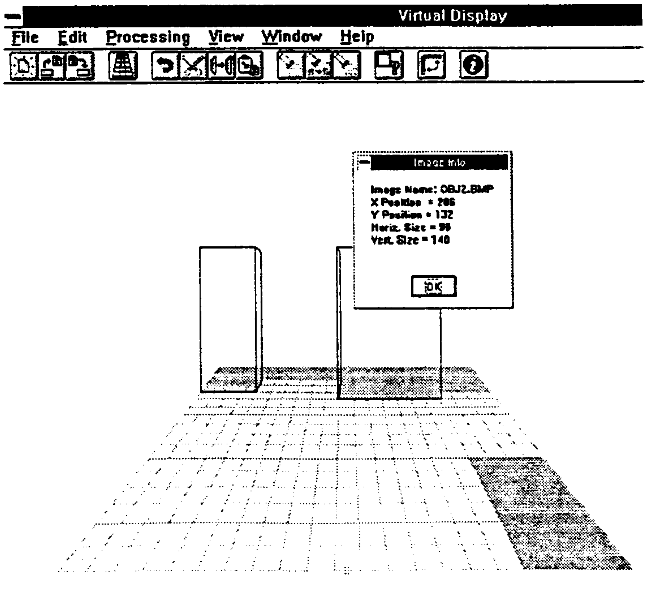


Fig. 9. Pseudo 3-D display of the explored room containing wire-frame models and raster images of objects.



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Y Position = 132
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Vert. Size = 140

Fig. 10. The computer graphics software environment provides on request position information about any object represented in the 3-D world model and allows the teleoperator to move objects in this scene by modifying their position parameters in the object information window.