3-D SENSOR SYSTEM

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ABSTRACT

Vision systems are inevitable components of intelligent and automated construction machinery. 3-d vision systems are proposed to provide advanced machine capabilities such as collision avoidance, robotic manipulation, terrain mapping, and more. The range images generated by 3-d sensors substantially facilitate robust, real-time data processing required for intelligent and automated systems. A 64 x 128 pixel imaging, infrared 3-d laser sensor is presented.

1. INTRODUCTION

The automatic and robotic construction machinery of the future will need vision systems to improve safety and efficiency. A vision system capable of detecting obstacles can avoid collisions and thus improve safety. Efficiency of machinery may be increased by automating certain tasks, such as motion or manipulation. Automatic motion requires knowledge of the robot's position with respect to its environment. Similarily, manipulating objects requires classifying these objects and recognizing their position and orientation. A vision system provides the necessary input for determining relative positions and orientation of robot and environment.

In this paper, 3-d vision system technology is presented, and its use with construction machinery is recommended. In section 2, the principles of 3-d imaging are outlined, and the inherent advantages for machine vision are exposed. It is concluded that 3-d sensors are desirable from a processing viewpoint, i.e. if robust and fast geometric scene interpretation is required. Section 3 presents 3-d sensor technology at Dornier. Specifically, a high resolution imaging laser scanner based on the time-of-flight measurement principle is described. The performance of modern 3-d sensors is illustrated. Section 4 is concerned with the processing of range images. In particular, applications pertaining to construction machinery are discussed.

2. PRINCIPLES OF 3-D IMAGING

In this section, the inherent properties of range images are exposed with automatic data processing in mind. Actual measurement techniques for obtaining real range images are discussed in the following section.

The principle of a range image (generated by 3-d sensors) as opposed to an intensity image (generated e.g. by CCD-cameras) is illustrated by figure 1. The numerical value associated with any pixel P' of a digital range image indicates the range r between the sensor S and the corresponding object point P. A range image is thus defined by the geometry of the viewed scene; it is not dependent on additional physical factors such as exterior illumination, atmospheric transparency, reflectance of object surfaces, orientation of object surfaces or light emission by an object. This property of range images is called "invariance".

Intensity images, on the other hand, are not invariant. The numerical value associated with any particular pixel P' of a digital intensity image defines the intensity of radiation collected at P'. This intensity is dependent on all of the physical factors mentioned above. Hence an intensity image actually contains more information than a range image, and this information may sometimes be required. However, from this mixture of information it is extremely difficult to extract the geometry information which is vital for many applications.

Range images can be used to reconstruct the geometry of the viewed scene simply by transforming them into "3-d images". Employing the (known) direction of scan $\mathbf{n}_{ij}$ associated with any specific pixel P_{ij} of the range image, a corresponding range value r_{ij} generates a 3-vector $\mathbf{v}_{ij}$ by applying the transformation formula

$$\mathbf{v}_{ij} = r_{ij}\,\mathbf{n}_{ij}.$$

The set of vectors $(\mathbf{v}_{ij})$ corresponding to a range image (r_{ij}) is called "3-d image". The scene depicted in the upper position of figure 2 gives rise to range measurements (r_{ij}); the resulting 3-d image is illustrated in the lower half of figure 2. Clearly, this 3-d image is easily processed for the detection of a vertical obstacle in front of the sensor (the wall of the building).

3-d images may be used to produce various representations of range images. If the vectors $\mathbf{v}_{ij}$ are used to define a 3-d surface, the representation shown in figure 3 is obtained. This representation exhibits the wealth of geometric information contained in a range image.

3. 3-D SENSOR TECHNOLOGY

A range imaging sensor system applicable in a construction environment must be rugged, simple to operate and fault tolerable. Specifically, this requires sensors with a high detection probability and at the same time, with low false alarm rates.

Active sensors, which are independent of ambient light, satisfy these basic requirements and are therefore prime candidates for construction applications. Most 3-d imaging sensors are based on active principles to generate their range data, although more or less calculation may be required to obtain range values for every pixel of the image. In addition, for a number of the range measurement principles (e.g. active triangulation) range accuracy is range dependent.

A method of generating range data directly from time measurements is based on the time-of-flight principle. Particularly suited is the light pulse time-of-flight measurement method, since it provides unique (not multivalued!) range data for each measurement. Furthermore, range accuracy is range independent. In conjunction with a scanner, sets of vectors $(\mathbf{v}_{ij})$ corresponding to a range image (r_{ij}) can be generated directly.

At Dornier, the development of the 3-d range imaging sensor technology, based on the time-of-flight principle, has been pursued for a number of years. Sensor systems have been developed for a variety of applications with medium and long range imaging capabilities.

For such systems, light pulse generation suitable for high range resolution (i.e.: short pulses) is most easily performed with laser sources. This allows, in addition, the implementation of coherent (i.e.: homodyne or heterodyne) or direct detection principles. For most robotic applications and in particular for 3-d sensor applications in the construction environment, direct detection suffices. It is thus possible to use multimode laser diodes as sources allowing the implementation of light weight, robust and fast imaging (i.e. fast scanning at high pixel rate) 3-d range imaging sensor systems.

As an example, results of a long range imaging sensor system are shown in Fig. 4 together with the reference picture. The range image (top right in fig. 4b) has its range values coded on a gray scale. (The lower right range image in fig. 4b identifies obstacles in this image by shading pixels belonging to obstacles. The left part of fig. 4b indicates the positions of these obstacles in a horizontal map).

To generate range images, efficient and rapid scanning technologies must be implemented. In order to produce range images from a fixed position or from a moving robot or vehicle scanning must, in addition, be accomplished in two dimensions. The resulting range imaging sensor may be called a "range imaging camera"[1]. Such a device, suitable for robotic application in construction environment, was developed at Dornier and will be described below.

The heart of the EBK is a fiber optic scanner performing a fast line scan. Fig. 5 shows the principle of this device. The injected laser pulse coming from a laser diode is reflected from a rotating mirror and imaged on to a circular fiber array which ends in a line array. On the receiving side the same process is carried out in the reverse manner.

The principle of the EBK is shown in Fig. 6. Here via the field optics, an oscillating mirror performs the column scan. The pulse source (laser diode), optical filter, receiver diode and time measurement and driving electronics are added to the basic line scanner.

This 3-d sensor has been realized and is shown in Fig. 7. On the right is shown a view of the scanner, on the left the closed EBK. The performance parameters of this system are:

Field of view	60° x 30°
Range image	128 x 64 Pixel
Image refreshing rate	1 Picture/sec
Imaging Range	8.5 m - 40 m

A scene imaged with the EBK is depicted in Fig. 8 together with a reference picture at bottom.

4. PROCESSING OF RANGE IMAGES

A 3-d sensor system with imaging capabilities is of use whenever vision is required. While video cameras provide vision also, man is required to watch the monitors. In contrast, the 3-d images generated by 3-d sensor systems lend themselves to robust and fast automatic processing. This reduces the workload on human operators or, in some instances, eliminates their need altogether. In the following, we shall give some examples of applications of 3-d sensor systems with intelligent processing in the construction environment.

A 3-d sensor system may be used as a stand-alone vision system. This system can aid an operator in calibration tasks. It can map the terrain of a construction site (i.e. measure the exact elevation of grounds), measure the size of holes, ditches, buildings etc., determine the precise absolute and relative positions of objects, and so forth. Such a system possesses a man-machine-interface (MMI) for the operator to input his inquiries and for the system to display the desired information.

In more advanced processing applications, the 3-d sensor system is a vision component mounted to some construction machine. This component may operate with or without MMI. For example, a crane may be equipped with a 3-d sensor system. Firstly, the system can monitor the operational environment of the crane for obstacles. The detection of obstacles will cause the system either to issue a warning for a human operator of the crane, or to automatically stop the crane. Secondly, 3-d vision can serve to automatically drop-off loads with great accuracy and efficiency. A human operator may have

1) Entfernungsbildkamera (EBK)

difficulty in estimating the precise position of a load with respect to the ground, particularly if he is far away or if his line of sight is obstrued. Eventually, the use of 3-d vision systems will allow for fully automatic crane motion; the operator merely tells the system where he wants a load dropped off (e.g. by remote data link).

Hydraulic manipulators constitute another example of construction machinery that require vision capabilities if they are to be improved. One major issue here again is safety. Consider a highly flexible manipulator for remote concrete deposition as shown in fig. 9. Its complete arm consists of six components, resulting in a large number of degrees of freedom. In a complex construction environment, it is a difficult task for an operator to redirect the arm from one position to another without risking a collision. The 3-d sensor system, consisting of the EBK (described in section 3) and a data processing unit, is used in this context to warn the operator of potential collisions. After the proposed motion has been entered, the 3-d sensor inspects the operational environment for potential obstacles, and the processing unit displays a graph as shown in fig. 10. In this graph, the letters A - F correspond to the components of the arm, and the four letters O, R, U, L (oben, rechts, unten, links: top, right, bottom, left) indicate the respective four sides of each component. The red areas in this display indicate where points of collision will occur during the proposed motion. The proposed motion of the arm is referenced at the lower left of fig. 10, in lateral and vertical views, respectively.

Another issue of importance for improving manipulators is automation. An advanced robotic manipulator requires each of the following capabilities:

1. accurate knowledge of its position and state with respect to its environment
2. obstacle detection for collision avoidance
3. object classification
4. object position determination (for robotic manipulation)

Note that each of these capabilities requires 3-d vision. Even in (1), vision is required to exceed precision limits imposed by dead-reckoning procedures. Fig. 11b shows a range image of the reference scene of fig. 11a. From such a range image, a 3-d image is immediately derived (cf. section 2). The 3-d image is readily processed to distinguish between regions in 3-space which are empty, and regions which are not. This information is sufficient for obstacle detection. For object classification, the 3-d image is segmented, yielding connected clusters of 3-d vectors. These clusters correspond to surfaces of individual objects. Correlation with 3-d reference models gives object recognition and object position identification. The range image of fig. 11b, for example, has been processed to determine the position of an airplane with great precision. Based on this knowledge, a robot can operate safely and effectively in the vicinity of the airplane.

CONCLUSION

Robotic construction machinery requires vision systems for safety and efficiency. Since the processing of video images is still in the state of research, 3-d sensors are recommended for robotic vision in current systems. 2-d imaging, high resolution laser scanners with frame rates exceeding 1 Hz have been shown to be reliable and powerful 3-d sensors in practice. Based on this technology, tasks such as the terrain mapping of construction grounds, obstacle detection and avoidance for mobile machinery, and partially or fully automated crane and manipulator motion have become feasible.

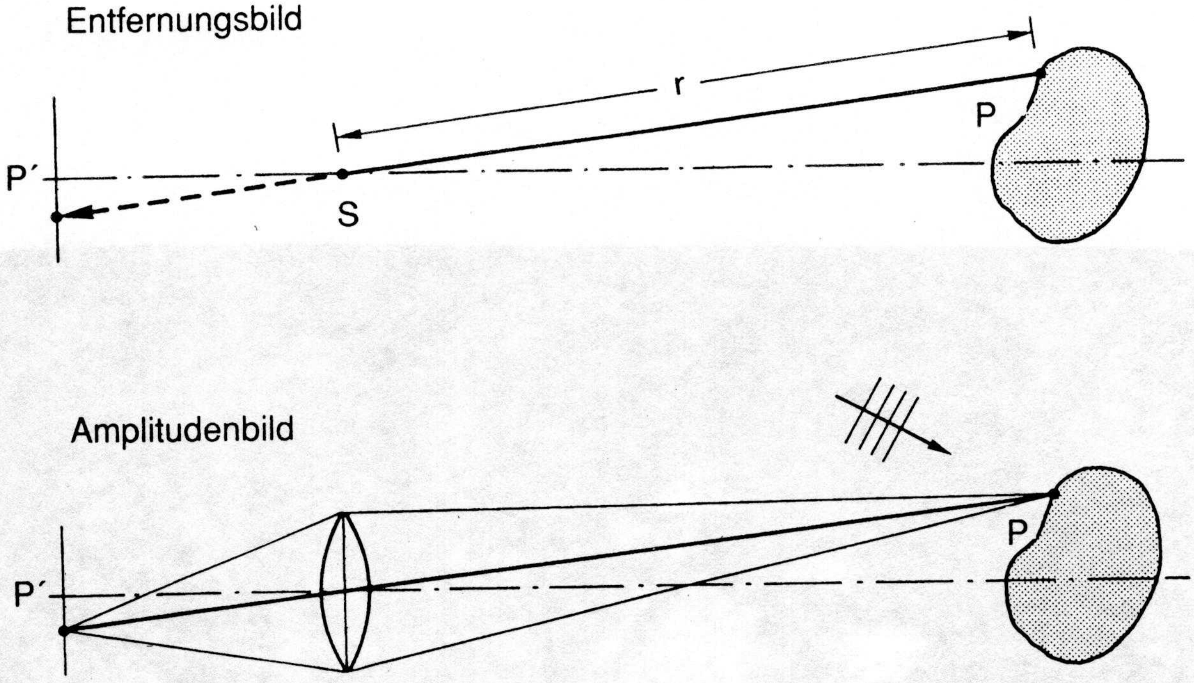

Fig. 1: Definition of range image

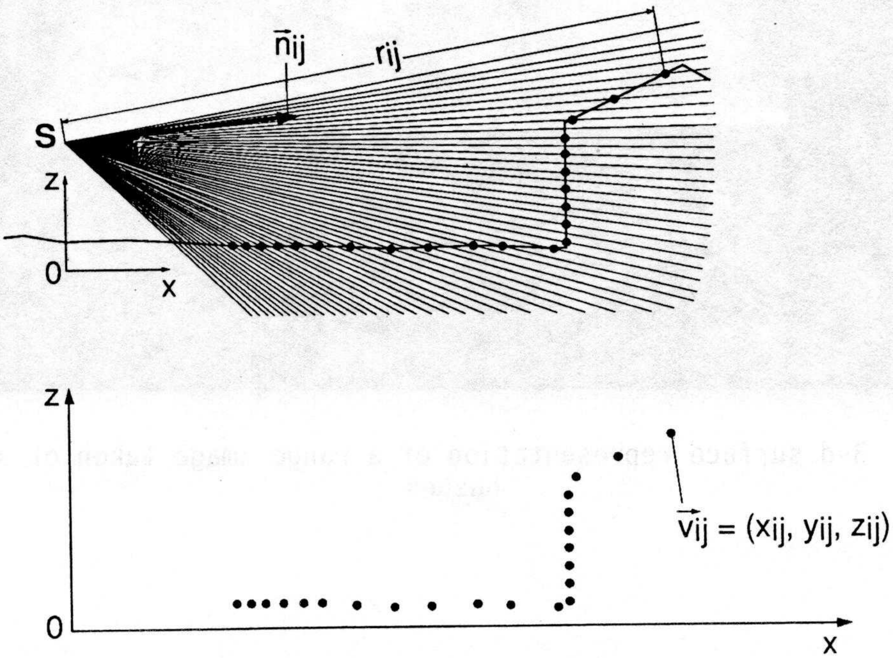

Fig. 2: Definition of 3-d image

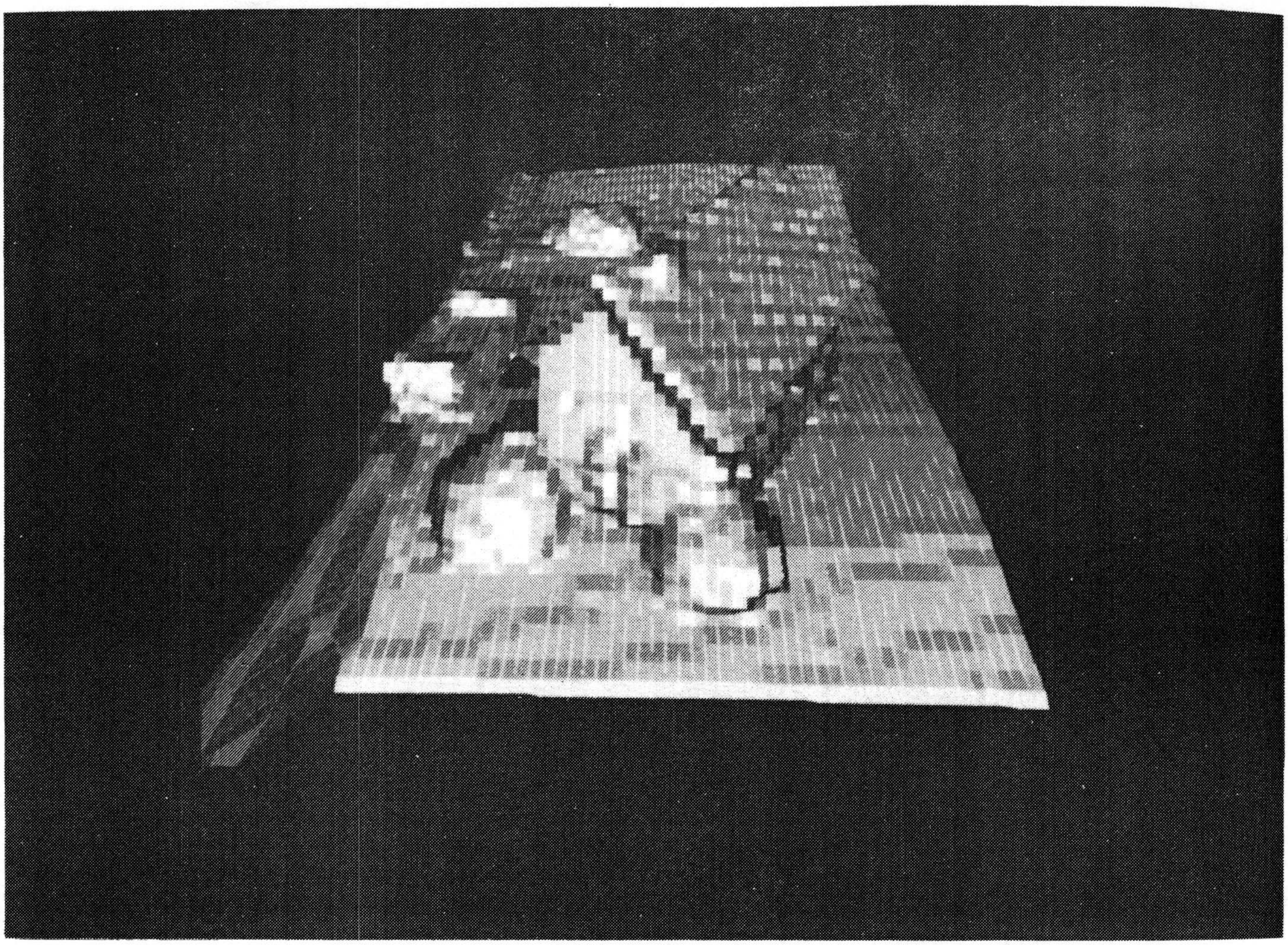

Fig. 3: 3-d surface representation of a range image taken of a house with bushes

Fig. 4a: Reference scene for range image of figure 4b

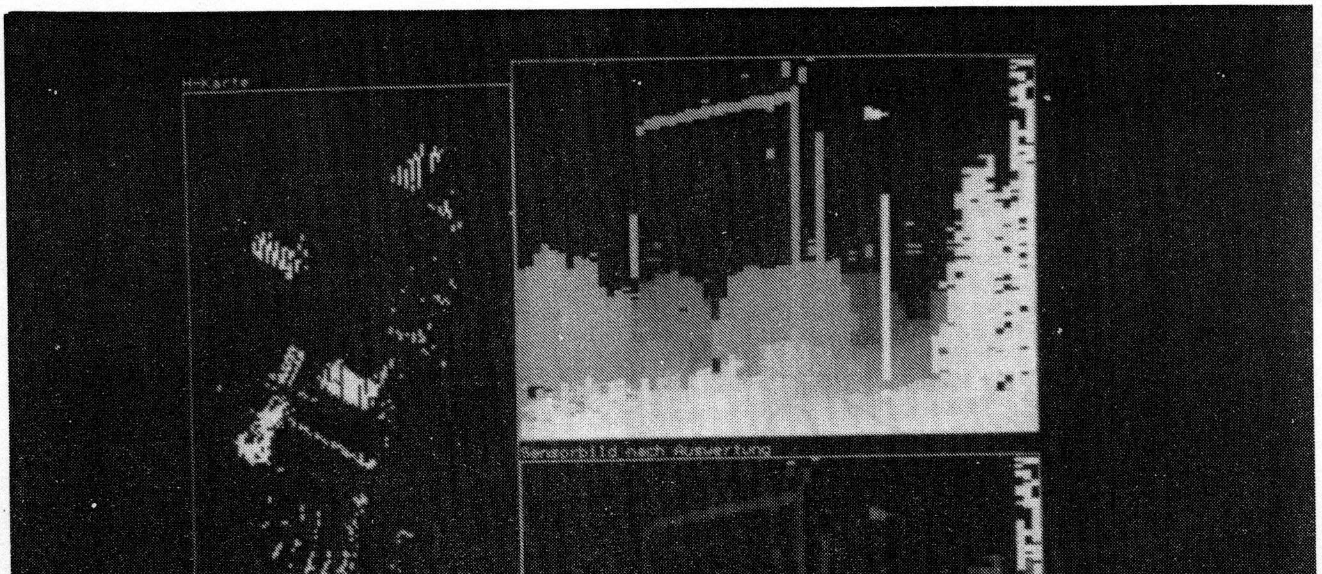

Fig. 4b: Graphical display of obstacle-detection system

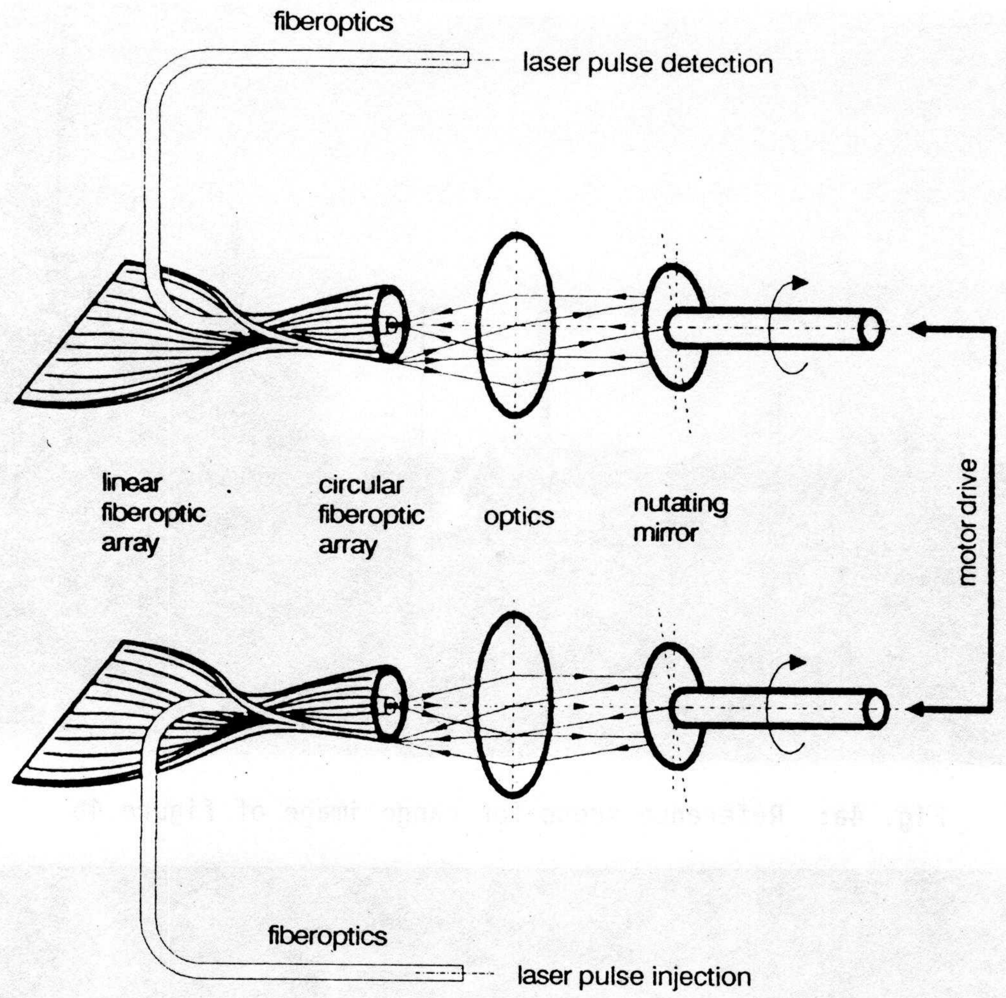

Fig. 5: Principle of fiberoptic line scanner

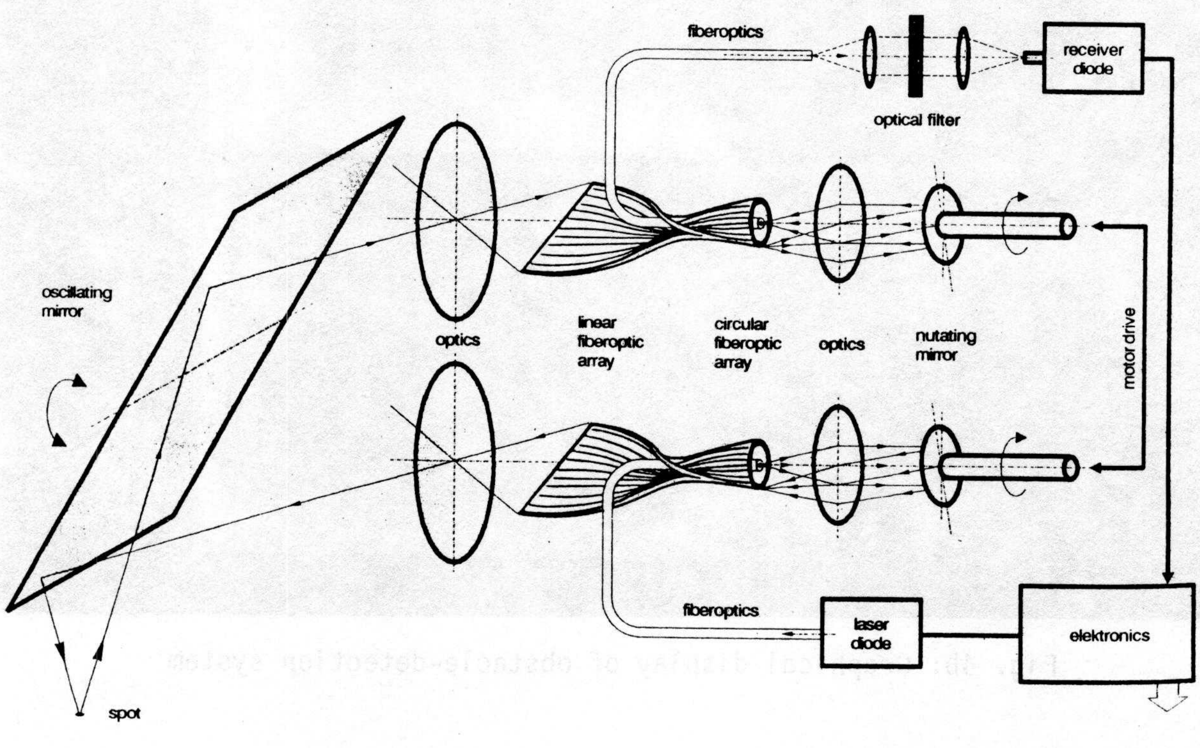

Fig. 6: Principle of range imaging camera (EBK)

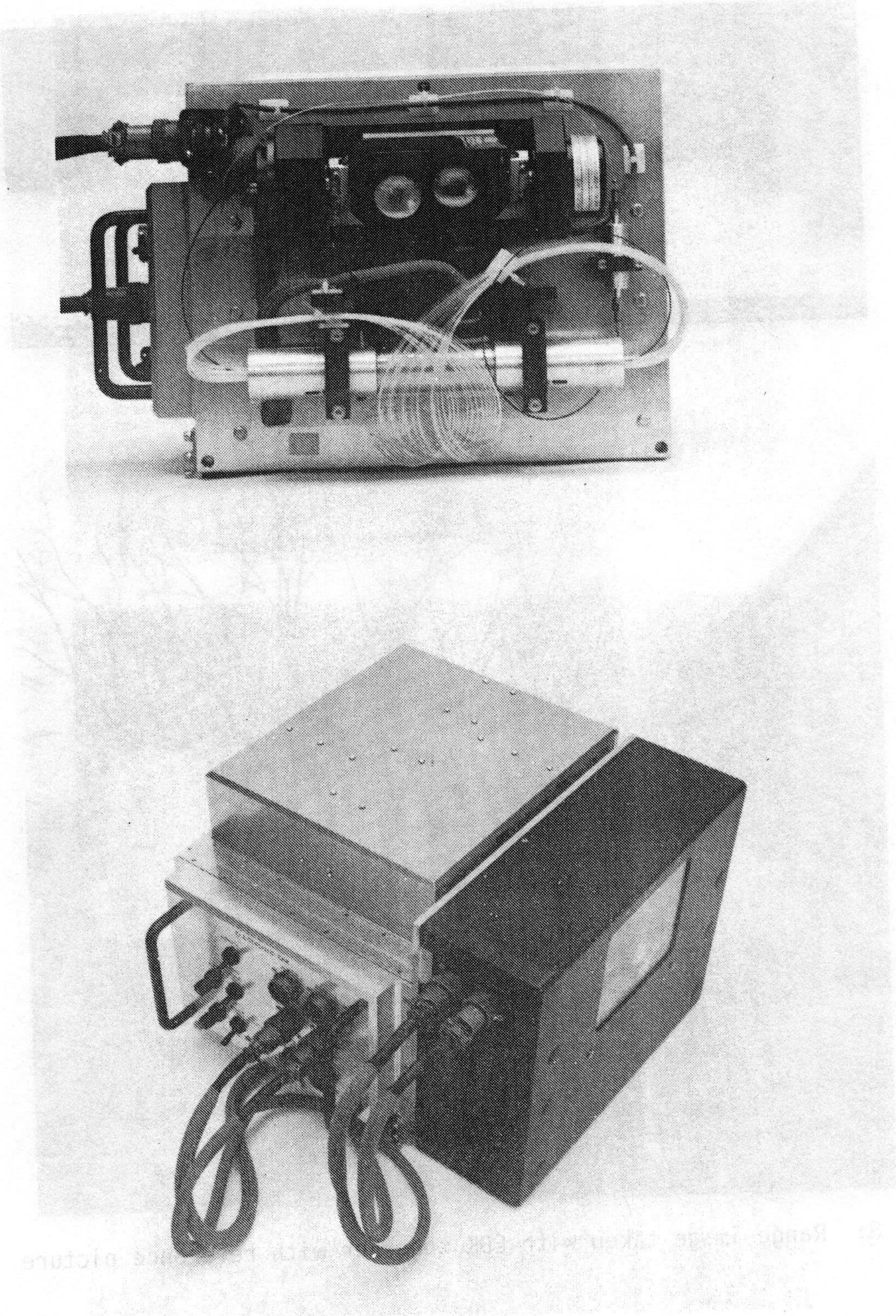

Fig. 7: Range imaging camera (EBK)

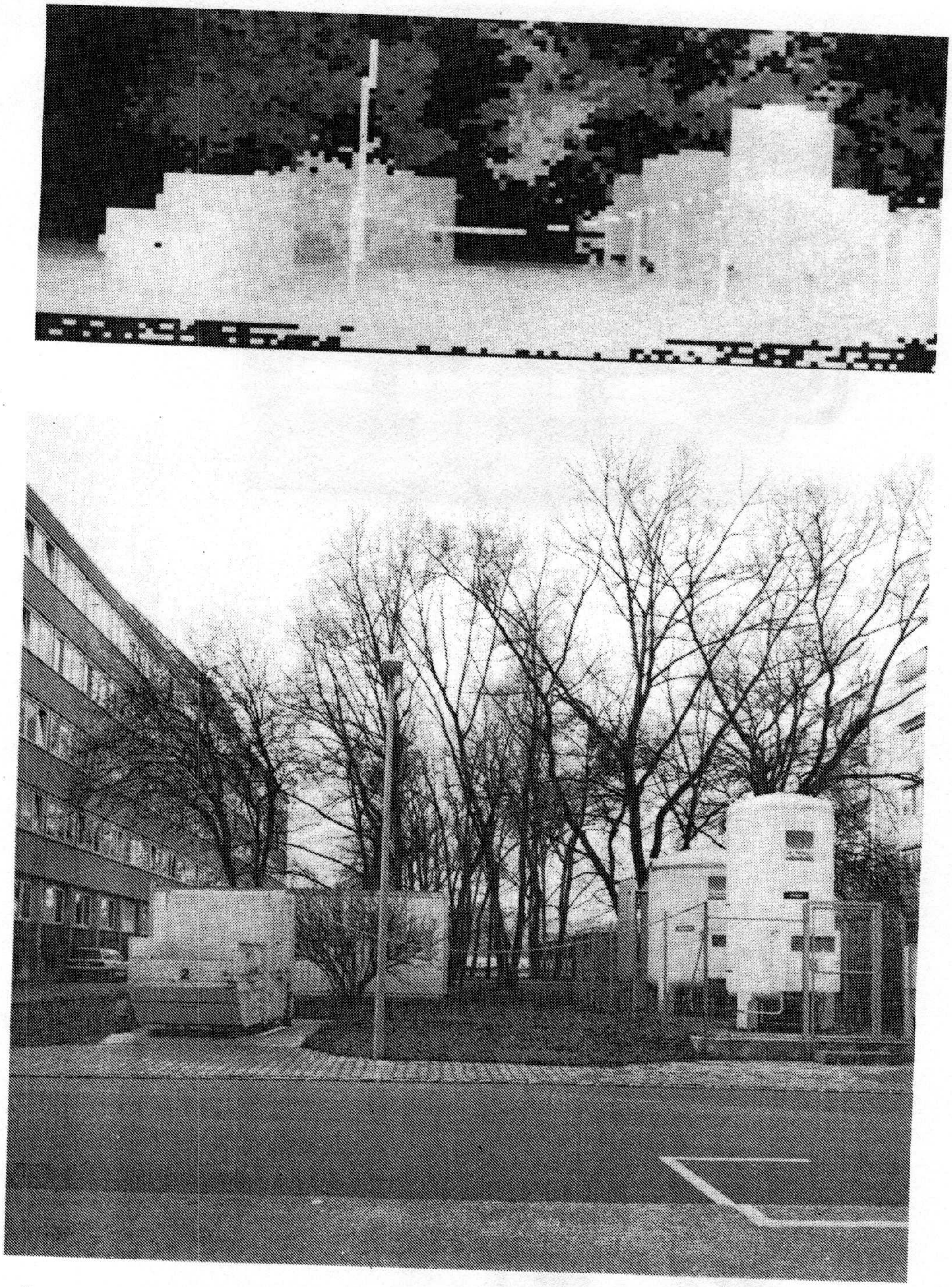

Fig. 8: Range image taken with EBK together with reference picture

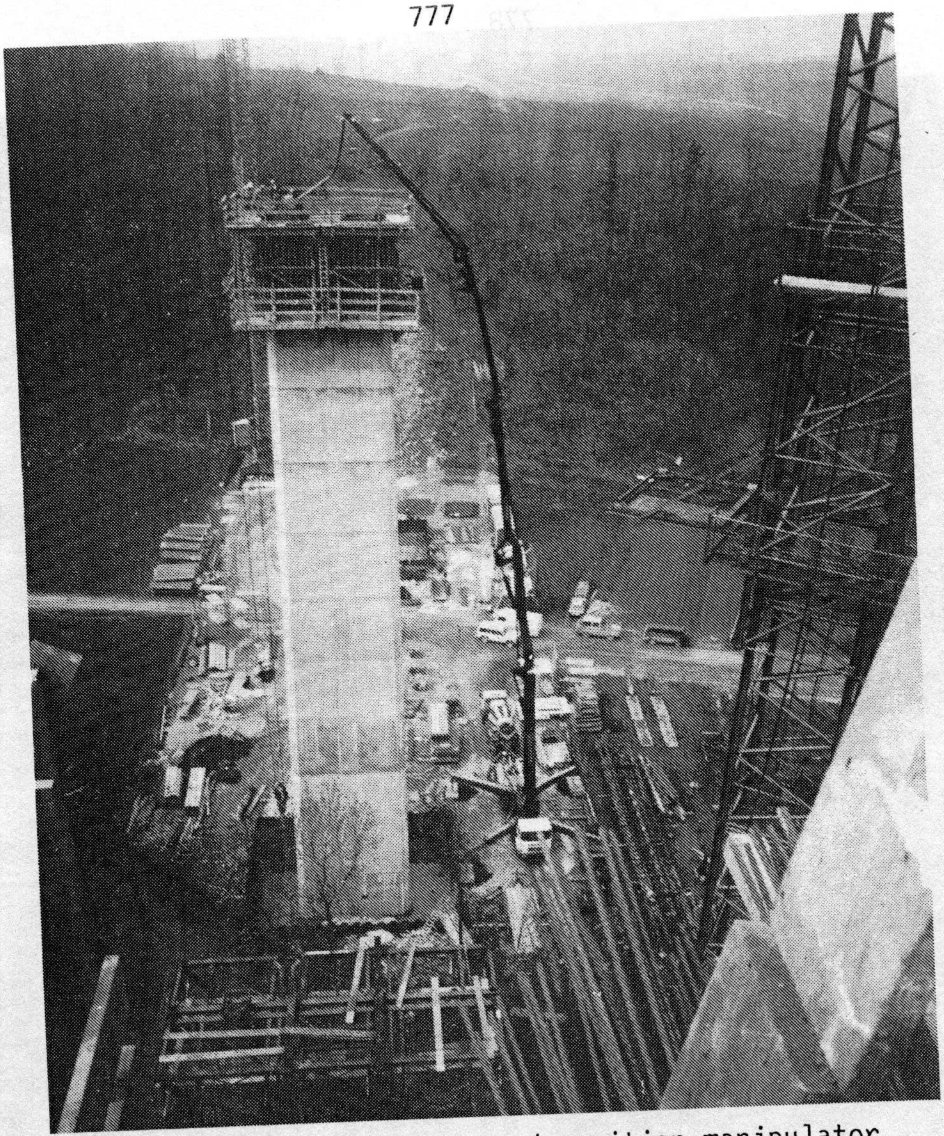

Fig. 9: Remote concrete deposition manipulator

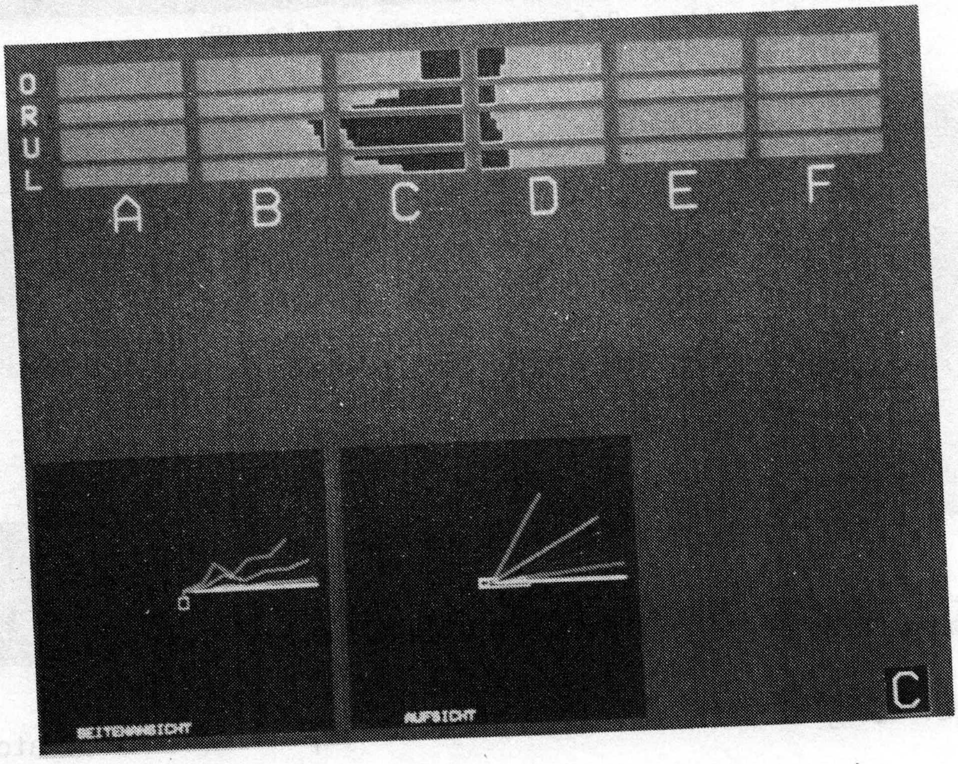

Fig. 10: Graphic interface for collision warning

Fig. 11a: Reference scene of fig. 9b

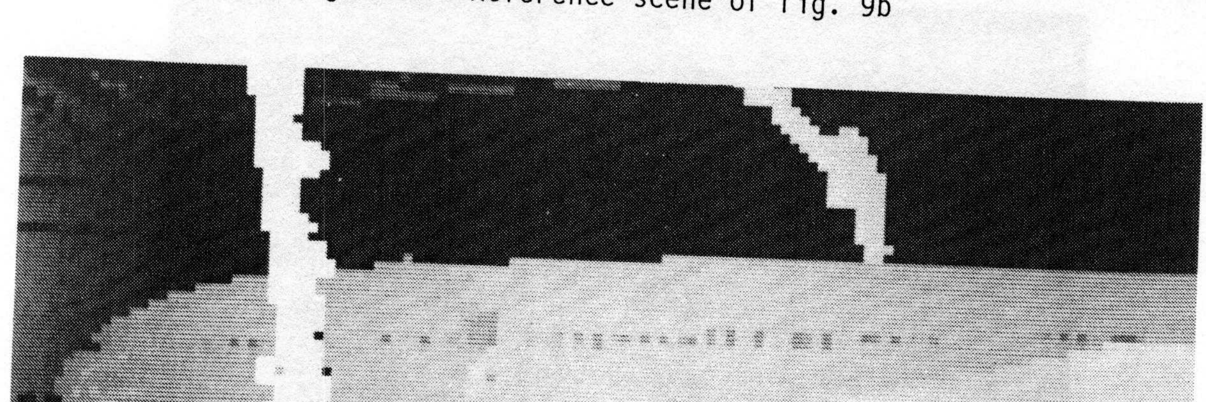

Fig. 11b: Gray-scale coded range image of airplane and manipulator