Increasing the accuracy of untaught robot positions by means of a multi-camera system

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Abstract—We aim to improve the absolute in line positional accuracy of a robot-guided effector to better than 1 mm. We do so using photogrammetric techniques and by relying heavily on simulations to fine tune each parameter and avoid weak configurations. We also use on simulations to design an LED calibration object adapted to this application. A test procedure enables us to validate both the simulated results as well and the calibration procedure. The test results exceed expectations by improving the absolute positioning of a robot effector by a factor of 20.

I. INTRODUCTION

Robots are currently one of the most important agents in industrial settings and perform many production steps. A more extensive use of robots is limited only by their accuracy restrictions. To be used as platforms for optical sensors, for example, the absolute accuracy of the position with respect to the pose of the end-effector has to be known more precisely than is actually possible. The current limit of an absolute position is in the range of 1 mm. Existing solutions, which aim at improving this situation are not able to control the robot during its activity. These rely on prior calibration steps, which cannot assure to correctly improve each position of the workspace at any time. On the other hand photogrammetric solutions are well known for their precision and flexibility, why is just strict to develop a photogrammetric solution allowing to control a robot and to extend its positional accuracy by least a magnitude of 10.

There is an increasing need for quality control of geometrical features (edges, holes and bolts) and surfaces (shell, scratches, buckles, etc.) in the industry. The goal is to automatically control each component part during the production process and immediately eliminate those with too large deviations from the model. This guarantees that all parts used for production lie within tolerances. Such systems can be found in many industrial branches.

Industrial robots are flexible and cost effective. As such, they can be used as mounting platforms for optical sensors which in turn can provide the desired geometrical features. The robot moves the sensor as a "moving effector" into different positions, and the features are successively measured and recorded. Therefore the position (the Cartesian coordinates X, Y, and Z) as well as the orientation (the three solid angles A, B, and C) required for the absolute coordinate measurement have to be determined.

The determination of the pose of the end-effector is possible with the knowledge of the kinematics of a six-edge articulated robot arm and the measurement of the shaft angles of the particular setting. The standard for robots is to measure angles indirectly via the motor position, monitored by a resolver. This may lead to measurement errors due to the clearance in the transmission system. In addition the kinematics of a robot result in unfavorable error propagation. Temperature also influences the precision of the results. Most robots are made of steel or aluminum. Once they are turned on, the metal warms up considerably on account of the heat of the motor and gearing. Thus an industrial robot does not offer the best conditions to realize high quality measurements.

Nevertheless, robot manufacturers have succeeded in optimizing the repeatability accuracy of the robots. Nowadays a repeatability accuracy of 0.1 mm can be achieved (0.2 mm for the established bigger robots with a maximum range of 2.5 m). But this accuracy cannot be guaranteed for long time periods in the case of a standard robot. Therefore additional techniques are required to enhance the pose repeatability accuracy. Also, appropriate methods are necessary to determine the absolute pose (e.g. calibration with exterior measuring devices).

II. SOLUTIONS FOR ACCURACY ENHANCEMENT OF ROBOTS

Improving the absolute positional accuracy of robots has long been a subject of investigation. First work was already carried out in the middle of the last decade. Improvements will be achieved introducing external physical measurements [1]–[3]. These activities are originated from and associated to the field of the manufacturer and consistently follow the idea to use different physical measurements, as are also essential part of a robot itself. In the context of a calibration, independent
external control information is used, like length and straightness of a beam, for example, making positional inaccuracies visible. Based on such error measurements a correction model can be developed, which is introduced into the motion control and modifies each individual position according to the error function.

The quality of these calibration processes can be substantive and reach the magnitude of a factor of ten. However it only can be realized as a pre-processing step, which has to be performed offline. It is an additional time consuming action, which only holds, when the error model keeps invariant during the activities of the robot. Risks of temperature variation or other external factors changing the robot model can neither be respected in real time, nor be detected.

This only can be avoided, if the robot itself is able to observe its erroneous position during its work activity. And as cameras are good instruments to observe spatial positions, research activities were directed towards photogrammetric concepts [4]–[7]. Most developments followed the idea to equip the robot head with a set of cameras observing certain reference information. The reference can be introduced by the object itself or by special installations, like a field of target points, being distributed in space.

When the object provides the reference, the calibration is performed in relation to the object itself. This improves the positional accuracy at the object and increases the quality of processing and might be sufficient, when the robot has a repeating operating process. But it can not be seen as an absolute calibration. This will be the case, when the reference comes from an external point field, which is observed by a set of cameras on the robot head. However, such solutions have their limits in the degree of improvement and the practicability. For practical reasons, the arrangement of the cameras has to be kept within certain spatial limits, why the positional accuracy will be restricted from the geometrical relationships between cameras and point field. In addition, the reference points have to cover a large space, when the position has to be observed in any operational situation of the robot. This would need huge installations, which are not very practical.

Newer developments provide tracking concepts for the effector on the robot or the head itself. Different approaches have been presented or are element of commercial solutions [9]–[12]. One idea uses the accuracy potential of laser tracker and extends the positional measurement coming from the tracker itself with optical solutions providing the orientation. This can be achieved observing reference points mounted on the object to be tracked. Such reference points can also act as single information, when a complete photogrammetric concept is realized. Then the target will be observed by a highly accurate calibrated camera installation, mostly consisting of two or three cameras. Both types of solution increase the positional accuracy of an instrument mounted on a robot head considerably. However, there are limits coming from the intersection geometry and from the dependence of the view direction of the tracking system. The accuracy is not homogeneous distributed over space and the head must be oriented to the cameras and cannot be observed in any operation state.

But in general, photogrammetric solutions have the potential to provide highest accuracy and the use of a photogrammetric conception should in principle solve the problem in a satisfying way. Already in an early stage suggestions were made to observe objects with a framework of appropriate arranged cameras [13]. And it could continuously be shown, that photogrammetric concepts are powerful to solve different problems in industrial applications [14], [15]. Although most applications aimed at the observation of an individual object by means of a set of images individually taken, it is also possible to precisely observe varying objects from a fixed set of cameras.
Fig. 3. Variation of point accuracy across line of sight (a) object close to camera baseline (b) object far outside camera baseline (c) object far outside camera baseline supported by a third camera

of cameras, which are mounted in a pre-defined way [16].

It is therefore logical to extend the idea of a general photogrammetric set up to the observation of an effector mounted on robot head. The success simply depends only on some well known rules, like a precise and stable internal and external set up of the cameras, an appropriate geometrical relationship between object and cameras to provide the accuracy requested and an object, which can be reliably observed in any position on the robot.

III. PHOTOGRAMMETRY BASED TRACKING

Photogrammetry is characterized by its flexibility and adaptability to individual problems. Photogrammetric image bundles have many parameters which can be adjusted in order to get an optimum with respect to precision, cost, robustness and practical framework.

Consequently solutions can be investigated under several aspects like number and arrangement of cameras, field of view, size and resolution of image plane, number and distribution of target points, size and dimensions of the operation space of the robot together with possible variations in the orientation of the effector. Such a large number of influences only can be led to an optimum by means of numerical simulations with appropriate decisions which follow eventual practical and/or economical constraints. But even without large simulations it is possible to show the impact of some major factors onto the quality. So it is evident, that due to the inherent triangulation principle quality decreases with increasing distance between cameras and object. Fig. 1 illustrates the point quality achieved by a two camera set up when observing an object in the foreground (Fig. 1a) and in the background (Fig. 1b).

A look at the error ellipses shows a strong decline of accuracy along the line of sight. This gives a heterogeneous quality for calculated object points, when their distance to the supervising cameras varies significantly and is not an ideal precondition for a tracking solution. Some existing commercial systems [8]–[10] (cf. Fig. 2) are designed in a similar way, which is why they suffer from a strong accuracy variation over the work space. This structural deficit can be eliminated with a more flexible arrangement of cameras, as by introduction of a third camera laterally observing the object space (Fig. 1c), for example.

Similar effects have to be observed concerning objects to be measured in positions largely apart from the baseline formed by the cameras (cf. Fig. 3a, 3b). The coordinate component perpendicular to the base line direction is worse by a factor of two or more due to the geometry of the intersecting rays. This leads also to a heterogeneity of the point quality in a systematic and undesired manner and only can be compensated by more flexibility, as shown with a third camera at the side (cf. Fig. 3c).

These two simple considerations already show clearly, that there is a strong interrelation between point quality and design of a photogrammetric solution and that there is the need but also the possibility to adopt a set up to requirements of a tracking task. Other major aspects in such an adjustment process are size of the volume to be tracked, number of cameras and their distribution in space, field of view of a camera, size and resolution of the image space and the accuracy limit to be hold in the tracking process. As other factors exist also and have their impact onto the tracking quality an optimum can simplest been found by a numerical simulation.

In order to demonstrate the potential of a photogrammetric design such a simulation has been performed for a work space of 4 m$^3$ (width: 2 m; height: 2 m, depth: 1 m).

This space has been spatially designed together with the free space available for installation of all cameras and the object to be tracked (cf. Fig. 4). Then, all main parameter e.g. number and positions of cameras, view angle, size of the reference body and so on have been optimized.

Targeted accuracy was 0.1 mm (at 2 sigma) for a tracked position of an effector and 0.2 mrad for the angular position of the effector. This distance has been assumed to be at most 500 mm and fits
well to size and design of effectors like in-line sensors, for example.

One important first choice is number and type of cameras. Table I gives some values for a 2 MPixel sensor and a 4 MPixel sensor. We see that all configurations are close to the angular accuracy required, but the amount of cameras used varies. This shows, that different configurations are exchangeable to a certain degree, but those with larger image frames are superior, what is evident due to the larger amount of image information available. Accordingly a camera arrangement as shown in Fig. 4 gives a good base for a precise tracking.

Another aspect to be documented from table I is that limits for a positional accuracy are much simpler to hold than those for angular precision. From a geometrical point of view this is evident, because the angular accuracy is derived from a certain number of points and depends on their spatial distribution and positional quality. This must be lower than an individual point. The degree of reduction depends on number and arrangement of points on the target used to signalize the effector. Some other calculations clarify this relation.

Table II documents the influence of the number of object points mounted on a target to be tracked. The stabilization of the accuracy with an increasing number of signal points is visible; however it is achieved at the cost of a considerable cumulation of the number of signals. In addition there is no difference between positional and angular accuracy. For both factors the increase is the same.

This impression changes for the spatial distribution of the object points tracked. The larger the distance between the points to be tracked, the better the angular quality, what is similarly evident from the geometrical point of view. The configurations shown in table III vary from 5 cm distance to 100 cm. Although this result is not surprising, a numerical simulation gives a reliable base for the practical design and avoids weak set ups.

As a consequence a reliable tracking needs not only a flexible arrangement of cameras, but also a tracking object of adequate size and with a sufficient number of object points to be determined. A geometrically ideal object serving for these purposes is formed by a sphere. It gives not only good preconditions for a homogeneous distribution of tracking points but also good geometrical frame work concerning the line of sight from the cameras onto the target object. Therefore a spherical object has been designed to house all necessary target points (cf. Fig. 5). The size of this target object, the number and distribution of the signal points have been chosen according to the findings from the simulations.

Besides of those factors already considered there are other elements affecting the accuracy as shown in table IV.

Taking all these factors into account our final simulations for a four camera configuration ended up with a theoretical
Accuracy of the effector position of 0.06 mm (one sigma). This result is based on a conservative assumption for the image accuracy (quality of image operators) of 1/10 of a pixel. The accuracy is evenly kept over the whole work space, as shown in Fig. 6.

Other assumptions for this configuration are:
- standard deviation of 0.15 mm for the positional accuracy of the cameras;
- standard deviation of 0.06 mrad dev. for the angular accuracy of the cameras;
- standard deviation of 0.05 mm for a signal point on the target object.

These assumptions correspond very well to typical accuracies to be achieved in photogrammetric triangulations. Therefore these simulations should give a reliable assessment of the accuracy potential for such a photogrammetric solution and confirm that the desired level of accuracy is achievable.

Practical tests then have to prove that the underlying assumptions have not been too optimistic and that this quality for a pose determination will be held in reality (cf. section V).

IV. DESIGN OF A TEST INSTALLATION

A. General setup

As explained, the solution is based on a set of cameras observing an appropriate signalized reference and target object. Each set up can individually be adapted and scaled to the needs of the volume to be controlled. Simply the number of cameras and their distribution in space has to be changed. The cameras have to be arranged in a way that the target body installed on the robot head will be seen by a sufficient number of cameras for all used poses.

The target body was realized with the help of active, i.e. self-luminous, target points homogeneously distributed in space. Active targets have the advantage of being simply switchable, what helps to introduce point codes by a switching sequence. External lights are not necessary, which largely extends the flexibility of the whole systems, since no special preparation have to be made in order to assure overall optimal illumination of the tracked body. Also, spurious daylight can be considerably suppressed by the use of infrared light.

For the actual test installation a measurement volume of 1.0 m × 2.0 m × 2.0 m (width, length, height) is assumed, which is a typical size for a robots’ operational range in the automobile industry (cf. Fig. 4). The volume will be observed by four cameras, arranged at the corners of a vertical square with four meters edge length, located about two meters behind the measurement volume. Four mega-pixel Firewire cameras were used in order to guarantee the required resolution in the pictures. Each camera is equipped with a lens with 12.5 mm focal length, resulting in a view angle of about 85°.

Figure 5 shows the realization of the active target body, which is installed on the robot head directly behind the effector. Each single target point is precisely fitted onto a stable support structure and contains an infrared LED. An integrated diffuser assures together with the mechanical design a homogeneous illumination characteristic.

The support structure for the active targets, all in all up to 54 pieces, consists of two half-spherical shells made from aluminum. Its surface consists of 9 plane ring segments with six tapped holes each in an angle distance of 60°, where the targets bolt down. The ring segments have been designed in a way that all targets lie on a spherical shell, and are evenly distributed in space.

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<th>Table I</th>
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<td>Change of accuracy in relation to type and number of cameras</td>
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<td>Chip size (MPixels)</td>
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<th>Table II</th>
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<td>Change of accuracy in relation to the number of object points being tracked</td>
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<td>Number of points</td>
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<th>Table III</th>
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<td>Change of accuracy in relation to distance between object points being tracked</td>
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<td>Distance (mm)</td>
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<th>Table IV</th>
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<td>Other factors influencing the tracking accuracy</td>
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Fig. 6. Error ellipses of theoretical accuracy for the effector position within the measuring volume. (a) Top view. (b) Front view.

As the targets do not have an optical visible code, they will be distinguished by a switching device, when necessary. The point controller itself is connected to the control PC by a 100 MBit Ethernet connection. The controller provides means to operate the targets via PC. It is possible to switch them on individually, in groups or all together.

B. Processing steps

Several processing alternatives have to be implemented in order to consider all practical conceivable situations:

1) Camera calibration
2) Camera orientation after a new installation
3) Camera orientation after small modifications
4) Inline pose determination
5) Inline control of the system

1) Camera calibration: The camera calibration follows well known strategies and uses the robot as supporting element. In contrast to all other processing steps during calibration a standard panel with coded and non coded passive targets is used. This simplifies the procedure as the panel provides a great number of points being necessary to get large and stable image bundles. Furthermore, the conventional coding of the points is much faster compared to a sequential switching of active targets. The robot is integrated into the procedure as he carries the panel and exposes it under varying orientations to each individual camera, in order to get the network of bundles needed for the triangulation.

2) Camera orientation after a new installation: All subsequent processing steps use the target body which will be moved and exposed by the robot at certain spatial positions. Depending on the state of the system – new set up (A), modified set up (B) or measure ready set up (C) – three different situations for the cameras will exist (A: unknown orientation, B: preliminary orientation values, C: exact orientation values). The procedure varies according to these conditions. Case A is the most time consuming, as no prior knowledge for the images is available, which might simplify certain calculations. Therefore the robot moves the target body to 7 different spatial positions and exposes all LED individually. The cameras keep on capturing during this process and generates a summary image for all exposed LED at all positions. This guarantees a sufficient coverage of image rays and produces first estimates for the orientation values. However it is time consuming due to the sequential switching of the LED, but this required to solve the correspondence problem.

3) Camera orientation after small modifications: Based on the preliminary values from case A the final orientation can be determined. The preliminary orientation is accurate enough to reduce correspondence risks. It is therefore possible to simultaneously expose all LED-lights. This speeds up the process and allows a much greater number of robot positions. Actually 15 different positions are used providing about 300 image rays for each camera. The correspondence is solved from the preliminary orientation values and the position of the robot itself to get all individual LED coordinates.

4) Inline pose determination: Both inline processing steps belong to case C, with precisely known orientation values. They only differ in the aim to be followed. An individual pose estimation is the normal case, when the robot head has to be tracked. For that purpose the target body is observed from all cameras simultaneously. The calculation profits again from the fact that the robot knows its position. Further backing comes from the known geometry of the target body, which supports the triangulation process.

5) Inline control of the system: An inline control simply assures a mean to check the system during a longer activity period, when it seems to be useful to control the geometrical state. This is made by means of reference distances, which are defined on a precise control bar also equipped with active target lights. All steps are supported by certain image processing tasks. These have been implemented under two main aspects: accuracy and robustness. The former will be
assured by state of the art point detection tools, like center of gravity, least squares or a functional contour determination. The use depends on the size of the individual target images and can be varied as needed. Robustness is at first assured by the optical design, which uses active infrared lights. This reduced the effect of ambient light and the impact of other optical relevant factors. At second, the detection is supported by preliminary values from the robots position, which narrows search areas and reduces the risk of wrong correspondences.

V. TEST AND RESULTS

The practical tests focus on the interior and exterior precision of the system. Tests of the interior precision have been performed by the determination of 27 different head positions. For each position ten separate measurements were made. From these repetitions resulted a standard deviation of a position of 0.035 mm (one sigma), with a maximum out of all 27 positions of 0.10 mm.

Of greater interest and importance for the actual value of the positioning system is the exterior precision defining the system accuracy in the framework of an outer reference coordinate system (e.g. the measuring cell system). In order to simplify set up and testing load we have chosen a reference system defined by a laser tracker. In general a laser tracker has a very high accuracy of about 0.02 mm for a single 3D point. This is about factor of 5 superior to our needs and therefore sufficient for test purposes. The idea behind the test is to observe positions from the laser tracker and the cameras at the same time and to compare differences. The numerical evaluation will then be done based on distances between such observed positions. This avoids the necessity of datum transformations and simplifies the test. The spatial position of the robot head is represented by a reflector cross housing five reflectors for the laser tracker (cf. Fig. 7). Its size is adapted to the spatial extend of the tracking object observed by the cameras, in order to get comparable situations for the determination of angular and spatial pose. For the first tests the robot head was moved to six positions in the measurement volume and all pose data was collected (cf. Fig. 8). This sequence was repeated eight times. For each sequence the residuals between reference distance and the photogrammetricaly calculated distance were calculated (cf. Fig. 9). The results show a statistic average of the distance differences of 0.037 mm, a standard deviation over all differences of 0.070 mm with a maximum difference of 0.142 mm. Since a distance is influenced by two points, a single coordinate has to be better by a factor of 1.41. Accordingly the absolute quality of the photogrammetric tracking is about 0.05mm for a single point, which is a factor of 2 better than the original targeted value. The superior quality of a tracked position with respect to the coordinates provided by the robot itself is visible when the tracked distances are compared to those derived from the robot’s own coordinate system. Here the standard deviation results in about 1.5 mm, which pretty much corresponds to the expectation of the absolute positional accuracy of a robot of about 1 mm per 3D-point and is largely worse, than with the new photogrammetry based tracking system.

VI. FUTURE WORK: APPLICATION TO DATA REGISTRATION AND SENSOR FUSION

With such an accuracy in the placement of the end effector, a robot can be used as platform for optical sensors such as 3D scanners, multispectral cameras, and others, which are of increasing importance in quality control. The use of robots as a platform for such sensors enables multiple views of the same object to be acquired automatically. This is of utmost importance since a single view is rarely sufficient to capture
the full area of interest. A given object can also be documented by multiple sensors successively fixed on the same robot. But for complementary datasets to enhance one another, they must also be integrated in a single geometrical frame. This process is called data registration, and can be described as the integration in a common coordinate system of data acquired from different viewpoints, from different sensors or at different times. We believe that the photogrammetric tracking of robots with multiple cameras can be successfully applied to multi-view and multi-sensor registration, an essential task in sensor fusion [17].

Registration is usually performed in two steps: a coarse registration, where the relative position of the two datasets is approximately defined, followed by a fine registration. Registration procedures are based on one or a combination of the following:

1) numerical methods;
2) use of targets;
3) known sensor position.

Registration algorithms aim at minimizing the distance between the overlapping sections of contiguous views. A comprehensive overview of 2D registration techniques and algorithms is given in [18] and [19]. Coarse registration algorithms largely rely on feature extraction while the fine registration of point clouds is most often based on the iterative closest point algorithm (ICP, [20]). This algorithms requires no feature extraction, but needs to be correctly initialized through a previous coarse registration, so as not to converge towards a local minimum. It also requires a 20 to 30% overlap between contiguous views to perform appropriately. In the case of multi-sensor data, algorithms based on the maximization of mutual information (MMI, [21]) are most common.

Registration often relies on the use of targets such as those illustrated in Fig. 10 to increase the registration precision and/or automate the process. This is possible when at least three targets are present in each view, evenly distributed over the surface of interest. Feature extraction algorithms are much more precise when targets are used than when relying on natural markers of the object. In particular, it is extremely difficult to register smooth surfaces without the use of external markers, though these surfaces are widespread in newly manufactured products. Adhesive targets, however, may damage fragile surfaces. Also, the repeated positioning and removal of targets is time consuming. Positioning the targets next to the object can be a good solution, but this not adequate when acquiring multiple small, high-definition views of a large object.

If we have sufficient knowledge about the sensor position at the time of the acquisition, it is possible to transform the datasets into the same coordinate system without relying on neither feature extraction nor the use of targets. For this we must know both the exterior and interior orientation of the optical sensor. The interior orientation (camera parameters and distortion) can be determined through various characterizations similar to the orientation procedures described in section IV-B. These can be performed once before all acquisitions are carried out. If a positioning system is used, the provides the exterior orientation (position and orientation) of the sensor. Currently, this is mostly used for two-dimensional acquisitions (tiled multispectral acquisitions of paintings [22]). For such small systems, a positioning accuracy of 0.05 mm is achievable. However, the accuracy of robots in 3D space is typically two to four times worse, as presented in section I, and thus not sufficient to register datasets solely based on the positioning of the sensor. The ensuing registration however, can be used as an input to fine registration algorithms such as ICP. Since the accuracy of such registration depends on the acquisition sensors, how well they are characterized and how precisely their position and orientation is known, using the positioning information from photogrammetric tracking of the robot effector / sensor platform may remove the need for algorithmic optimization altogether. This procedure can also be used to register data provided by different optical sensors, successively mounted on the same robot, as long as the scene has not changed. This registration procedure eliminates the need of targets and can reduce the number of necessary acquisitions, since a smaller overlap is required to correctly register contiguous views. Relying on photogrammetry-based tracking to position a robot guiding an optical sensor can thus provide accurately registered datasets, with minimal hassele.

VII. CONCLUSION

The photogrammetric tracking of a robot end effector increases its absolute positional accuracy by about a factor of 20. This opens new possibilities to use robots as precise devices supporting measurement processes or other precision sensitive activities. Further advantages of this solution can be seen in the inline conception controlling the robot during his activity. This avoids expensive teaching and preparation steps and is free from any stability assumptions. Optical sensor can thus be accurately controlled by robots and the multiple acquisitions can be precisely registered, without the need to rely on targets nor optimization algorithms. Furthermore, this concept is scalable and adaptable to other configurations of the volume to be surveyed.

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