DEVELOPMENT OF A DEVICE TO PERFORM STAKING OUT PROCEDURES AT LARGE-SCALE ACCELERATOR FACILITIES

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Abstract
To speed up staking out of components at large-scale accelerator facilities and to make such work more ergonomic, a semi-automatic device is developed that only needs to be roughly brought to places where coordinates are to set-out on the ground for subsequent works like drilling. When brought into the proximate position, the development takes over and performs fine positioning and marking in an automated manner for all points within reach of the work area.

MOTIVATION AND INITIAL SITUATION
Staking out of components at large-scale accelerator facilities is a labor-intensive and time-consuming as well as recurrent task for each new experimental set-up. Until now such survey work is done by hand. In an iterative process, a hand-guided reflector is placed to the point to be staked out by means of a polar measuring system, e.g. a laser tracker. When the point is found, it is marked in an appropriate way. The process is hardly automated and physically stressful for the staff, especially when working in an un-ergonomic posture on the knees for hours. Consistent quality depends on the focus of the operators, especially if there is a large number of points, and thorough control requires repeated measurement of the points, however.

Looking more closely at the process of staking out, three steps can be identified:

A. A rough approach of the hand-guided reflector to the area of interest,
B. An iterative fine positioning, whereby the residual deviations must always be shown to the operator, and finally
C. The marking of the coordinate by hand.

The procedure must be repeated for each individual point. In the last few years, a lot of work has been done on fully automated mobile robots, so-called layout robots, which are able to transfer plans on a scale of 1:1 into a location. Examples of such robots are the TinyMobileRobots® systems [1], which are used for outdoor jobs, or the FieldPrinter® from Dusty Robotics [2], which is used in particular for the layout in high-rise and multi-storey constructions.

However, the use of fully automated systems in the environment of accelerators is currently inconceivable. This is mainly because during installation times an accelerator tunnel is normally filled with all sorts of installation materials in awkward locations. Therefore, to improve this conventional approach in terms of consistent quality, time requirements and ergonomics, a semi-automatic system is developed that, once brought to the proximity position, takes over work steps two and three for a certain number of points to be set out in the range of the system. In contrast to the two layout robots presented, the system is designed as a stop and go system.

Unlike the conventional approach, however, the process is not iterative, but the points are approached and marked immediately. The special conditions in tunnels and test halls were considered in the design, as they are given at large-scale accelerator facilities such as DESY.

DESIGN OF A STAKE OUT SYSTEM
To create a system that is well adapted to the practical needs as well as flexible to use, a platform is developed, which has to be moved by hand to places with points to be staked out. The entire further process is then fully automated and as such delivers results with consistent quality. Accordingly, the system consists of the following three basic elements:

• A mobile platform, that can be moved manually to the different places of interest,
• A guidance system that connects the superordinate coordinate system with the local coordinate system of the platform and
• A measuring device at the platform for fine positioning as well as a unit for making of points.

The guidance system used is a laser tracker, with which accelerator facility personnel are already familiar and which provides the required accuracy. The first step before staking out always consists of a free stationing of the tracker. Geodetic monuments with known coordinates are part of the standard infrastructure in the tunnels and test halls at accelerators. Extensions to the infrastructure are therefore not necessary in order to be able to use the developed stake out system immediately.

The mobile platform
A stake out trolley, which is constructed similar to a shopping cart (see Fig. 2), serves as a carrier for the marker unit. On the one hand, the trolley must be maneuverable, easy to steer and lightweight as well as robust to transport, on the other hand, it must provide a stable stationing to perform fine positioning and marking.

Four free-running swivel wheels allow the platform to be moved easily in any direction, but simple brakes are not sufficient to keep the platform on place for staking out. Instead, an electronic lifting mechanism is installed that can lift the platform on three supporting stands within a few seconds. The mobile platform carries a power supply that serves to power the individual components as well as
the lifting mechanism. The capacity of an 8 Ah replaceable battery is sufficient to guarantee autarkic operation of the system for several hours.

While the individual components are operated by the control program, the lifting mechanism is detached from it. Due to this setup, the laser engraver always has the same distance to the ground. It can be controlled by a rocker switch mounted directly on the control panel. This makes it very easy to bring the platform into the correct starting position for staking out. During the initialization process, the software determines pose of the platform. This initial position and orientation are considered at the control of the marking system, so that correct positioning is also ensured for non-horizontal floors.

**Fine positioning and marking**

Manual marking is typically done in a tactile way by pen or stencil, but for obvious reasons this type of marking is not suitable for an automated process. A mechanical marking with e. g. a centre punch is ruled out, as this would unnecessarily stress and influence the complete system. Colour marking by spraying does not provide the desired sharpness of the marking, especially since it must always be expected that there may be dust or other impurities on the floors.

The approach for the developed system is the use of a laser, which allows non-contact engraving. The laser can be used to engrave sharp marks into the top layer of the industrial floor with high precision and without any wear effects on the marking tool. However, lasers for such tasks belong to laser protection class 4, which means that even reflections of the laser beam can be dangerous to eyes [3]. Accordingly, the laser must be protected via housing and the system must include a shutdown device as soon as there is a risk of laser light escaping in an uncontrolled manner.

The device for fine positioning and marking on the mobile platform corresponds to a stationary robot. In general, stationary robots have the task of positioning any effector via a kinematic chain [4]. The effector used is a suitable marking unit realized by a laser. The kinematic chain necessary to position the laser is implemented by two-dimensional Cartesian robot. The SMR is installed above the engraver on the carrier of the XY-robot. Common reflectors have a restricted aperture angle of approx. ±20° - ±30°. In order to enable continuous tracking, the SMR must be constantly aligned with the guidance system. Thus, a tool for automated reflector alignment is required, where it is sufficient to provide only a rotation around the vertical axis. This is called automated one degree of freedom (1-DoF) alignment. For this reason, a commercial system such as API Active Target™, which allows a two degree of freedom (2-DoF) alignment [5], is not necessary to integrate.

For the implementation of a 1-DoF system, a SMR nest is installed centrally on a brushless DC motor (see Fig. 1).

![Figure 1: Schematic of the automated reflector alignment system.](image)

The motor itself is speed controlled in a special control loop. The control loop needs a set-point for the SMR orientation. This seed-point changes when the position or orientation of the trolley changes. While position is given with continuous laser tracker measurements, the change in orientation is obtained via an integrated gyroscope on the mobile platform. Every time the trolley is repositioned and lifted to the stands, the determination of the different necessary transformation parameters takes about 30 seconds before starting to stake out.

**The stake out system**

Fig. 2 shows the schematic structure with the individual components and the actual implementation. The trolley with a stable frame has a size of 1200 mm x 600 mm. The fixed handle at the back end can be height adjusted and retracted to ensure easy transport. Directly fixed to the frame are the swivel wheels and three stands for the lifting mechanism.

In the front, the XY-robot is installed in its individual frame for stability reasons. On its moving part the laser is mounted together with its housing. Directly above is the device for the automated reflector alignment, including the SMR. Beneath the control panel, the gyroscope, the driver for the motors of the robot, and the power supply are installed. Standard components are used as far as possible.
WORKING PROCEDURE

For the control of the measuring system the software SpatialAnalyzer® is used. In principle, any laser tracker or total station that can be controlled with SpatialAnalyzer® can be used to control the stake out trolley. The setup of the system is the same as for conventional work, with the difference that an UDP port is opened for the permanent transmission of the measured data of the laser tracker to the robot program. The measurements of the laser tracker are transmitted wirelessly to the control panel. A soon as the tracker is coordinated in the superordinate coordinate system and the laser beam of the tracker is aimed at the SMR, the system is ready to start.

The general procedure of the program and the single processes are shown in the flow chart in Fig. 3. The implementation was done with the software LabVIEW® and a MATLAB® plugin. The program is divided into an initialization phase, in which the individual components are connected and initialized, and the main program. Here, both the positioning of the carriage and the automated stakeout of the individual points are realised.

Program launch

After the start of the control program, an initialization file is loaded automatically. It contains parameters for various settings and the necessary information for establishing connections to the individual components onboard the platform and as well to the guidance system. If problems occur during the connection setup, it can also be carried out manually. After all components have been successfully connected and initialized, the coordinates to be staked out as well as the laser tracker position are loaded. Only then the entire system initialized. This initialization includes the following steps:

- Homing of the Cartesian robot
- Drift determination of the gyroscope
- Determination of the transformation parameters
- Setting parameters for automated reflector alignment

During the first two steps, the zero-axis positions of the XY-robot and the drift of the gyroscope are determined. While the zero positions remain unchanged, the drift determination is updated later at regular intervals.

The procedure for determining exact transformation parameters consists of moving the reflector with the XY-robot to a series of predefined positions. At each of these positions a measurement is taken with the laser tracker. The measured points are then used to determine the transformation parameters between the robot system and the laser tracker system, resulting in the initial pose of the trolley. It should be noted that an eventual tilt of the system is determined solely from the measured coordinates, not from an additional tilt sensor. Modern accelerators are often built "laser-straight" and thus do not follow the curvature of the earth. In this case a tilt measurement based on gravity would give wrong results. Based on this initial pose, parameters are set for the automated reflector alignment.
Main program

The main program can be divided into two separate tasks. The first one is the automated reflector alignment. It is performed continuously in its own loop and does not require any control by the user. The second task is the staking out of the coordinates. This happens semi-automated in a second loop.

First, the trolley must be manually guided by the user to the points to be staked out. For this purpose, the locations of the individual points to be staked out, the trolley and the laser tracker are displayed in the graphical user interface of the program. Movements of the platform are detected by the laser tracker and the gyroscope, and the readings are used to update the display. Thus, the operator is always provided with relevant information.

Based on the current pose of the vehicle, as well as the status of the points to be staked out, each point is highlighted in three different ways and updated at regular intervals:

- **Red:** Point is not staked out and not in working range.
- **Yellow:** Point is not staked out but in working range
- **Green:** Point is staked out.

If there is at least one point within reach of the XY-robot, the platform can be raised onto its stands, and the automated stake out can be performed.

For this purpose, the transformation parameters are determined using the same procedure as in the initialization. Based on the determined parameters, the positions for the XY-robot to enable marking of the individual coordinates to be staked out are calculated. Equation (1) describes the calculation of the position of the XY-robot \( X_R \) for the marking of a point \( X_W \) that is given in the superordinate coordinate system:

\[
X_R = t + RX_W - k
\]  

(1)

The first term of the equation corresponds to the transformation of the points to be staked out into the XY-robot coordinate system. \( t \) denotes the three-dimensional translation vector, \( R \) the 3 x 3 rotation matrix. Roll (\( \psi \)), pitch (\( \phi \)) and yaw (\( \theta \)) angles of the XY-robot can be derived from it. The vectors \( k \) and \( d \) describe two correction terms. The offset between the center of the SMR and a point marked on the ground through the laser is given by \( k \). It is determined during a calibration. The influence of an oblique setup is described with the vector \( d \). It must be calculated for every setup.

The robot is then moved to the specified positions and the laser is used to engrave marks in the ground. For marking the points, different shapes are available, e.g. a cross or a cross with a circle, which can be scaled by the user. Alignment of the markers according to the superordinate system is possible. The status of the individual points is saved continuously in a separate file. Accordingly, a stakeout can be interrupted at any time, e.g. to re-station the measuring system.
CALIBRATION

The offset vector $k$ between the SMR and the laser footprint (see Fig. 4) must be determined to perform accurate stakeouts. The calibration to establish $k$ should be performed in the laboratory, but because of the simplicity of the procedure, it can also be used for system testing as part of a field calibration. In the event of a field calibration, this must be carried out on a level surface. The procedure is simple and can be carried out in advance of stakeouts. To begin with, the system must be initialized together with a laser tracker in the same way as for stakeouts.

Figure 4: Calibration vector $k$ in longitudinal and transverse view.

For the execution, the stake out trolley must be placed on a level surface on which markings can be made. The calibration can be started afterwards and consists of the following steps:

A. Determination of transformation parameters.
B. Automatic guiding of the carrier to defined positions, measuring the position of the mounted SMR, and placing a marker.
C. Removal of the trolley.
D. Manual measurement of the marked points with a transparent nest.
E. Transformation of the points measured in B. and D. into the XY-robot system.
F. Determination of the calibration vector $k$ with the transformed measured values.

FIRST TESTS

In the Laboratory

The achievable accuracy of the stakeout was investigated in the laboratory. For this purpose, points on surfaces with different inclinations were marked out using the stake out system in combination with an AT402. After that, an AT901 was stationed in the same superordinate system as the AT402 and the staked points were measured manually with a T-Probe. Table 1 shows the results of one measurement, where the inclination of the robot was given by $\varphi = 1.5441$ gon and $\psi = 0.6477$ gon.

<table>
<thead>
<tr>
<th>$X_N$ [mm]</th>
<th>$Y_N$ [mm]</th>
<th>$X_M$ [mm]</th>
<th>$Y_M$ [mm]</th>
<th>$\Delta_{XY}$ [mm]</th>
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<tr>
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<td>-758,29</td>
<td>0,19</td>
</tr>
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</table>

The result of the study is that stakeouts can be performed with an accuracy of 0.5 mm.

On Site

Despite still in development, practical tests at DESY were also performed. To test and to adjust the engraver, markings were made on different grounds. Information about the material expected or known for staking out can be entered in an input file in order to control the laser with regard to its intensity and speed. Depending on the material, marking a point with a two-by-two cm cross and a circle with 10 mm diameter (see Fig. 4) takes between 10 to 30 seconds. If several points are close together within the working range, a separate transformation does not have to be determined for each point.

Figure 6: Markings on different surfaces: a) Coated concrete floor, b) Fine-grained concrete floor, c) Coarse-grained concrete floor
As an option, not yet implemented, a point ID can be marked too. Of course, this will prolong the time necessary to stake out but would be suitable help for the subsequent drilling works.

CONCLUSION

The current development of a staking out system meets the particular needs at DESY. However, automation to the extent that the mobile platform moves independently is also conceivable, see [6]. Essential enhancements would be that the platform is motorized and that sensors are included for obstacle detection. Especially in environments with many existing installations, such automation is likely to be associated with many practical difficulties. However, the mass and repeated staking out of points is not only a challenge at accelerators facilities, also in factory lines at e.g. the automotive industry or in exhibition halls such tasks occur.

REFERENCES