Automatic rough alignment for key components in laser driven experiments using fiducial markers

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Abstract.

In the laser - solid target experiments at ELI-NP, maximizing the availability of the laser system and hence the number of shots during a campaign is envisaged. One of the factors that affects this is the time for preparing the experiment and the time for changing the targets between shots. In this paper we present a method for automatic rough alignment of various experimental setup instruments like the target frames, microscopes and diagnostics. Giving the impossibility to define a global reference system that captures precisely enough the relative position of all equipment in a continuously changing experimental setup, the method developed is using relative optical measurements using fiducial markers. The method is conceived to be used along with other micron-level alignment methods as a pre-alignment phase. Along this work, a setup and the algorithms were developed in order to test the accuracy of the method. First tests revealed a rough alignment accuracy between 100-200\(\mu\)m which was achieved using only a low resolution imaging camera. The accuracy can be further improved using higher resolution imaging systems or by developing new key points in the algorithm that are discussed at the end of the paper.

1. Introduction

For laser - solid target experiments where the accelerated particle beams require reproducibility and enhancement of the parameters (e.g. maximum energy, spatial homogeneity, angular distribution, energy spectrum), preparing and aligning the experimental setup, including the target is a highly demanding task. In general, running the experiments requires remote control as the interaction takes place in vacuum, while the generated ionizing radiation requires the shielding in heavy concrete bunkers [1].

Considering the high-repetition rate of current laser systems (on the order of up to tens of shots per second), the availability of the targets have to be also ensured. This can be affected by long experiment preparation times and by the fact that for changing the target it is required to vent and pump down the interaction chamber. For the first issue, when solid targets are used, the only solution is to implement fast alignment and target exchanging methods. The latter issue can be solved by using a target feeding system which stores multiple target frames under vacuum [2], [3].
The peak intensity of the laser on the target is a crucial parameter that can be affected by the deviations of the target position. For the case where tight focusing is used to generate high-intensity optical fields, the Rayleigh length of the focused laser beam is in the range of micrometers to tens of micrometers. So, in addition to fast alignment, very precise alignment is required.

At the ELI-NP facility, different experiments with multi PW laser beams will be operated [4], [5] with various equipment in the interaction chambers. The continuously changing setups lead to time consuming operation if manual pre-alignment and calibration procedures are used where physical absolute references (like metallic stalks or optical irises) have to be installed.

In previous works, absolute reference alignment methods have been developed achieving good results. The retro imaging system [6], [7], [8] uses the reflection from the target which is imaged back through the beam transport. The image produced by the target in the right position is used as reference image for positioning other targets.

The rear surface imaging method [9], [10], [11] uses a microscope for imaging the focal spot. Its focal plane becomes the reference for positioning the target.

The method was improved with the addition of a near-field and a far-field imaging for increasing the precision of orientation alignment [12]. For speeding up the alignment procedure, the microscope was improved by adding one extra optical systems with a lower magnification [13]. For increasing the accuracy, the microscope was coupled with multiple interferometers [14] achieving micron-level alignment.

Another solution was the use of a setup with three orthogonal lasers which create through three orthogonal holes Fresnel Diffraction images used as references for positioning new targets [15]. All these methods either use setups with fixed and well defined structure or need complex pre-alignment and calibration procedures which are time consuming.

In this work we introduce an automatic rough alignment method and positioning algorithm [16] based on a numerical real-time optimization procedure which aims to reduce the time necessary for preparing the setup of an experiment. The method is based on optical position measurements for fiducial markers which are used for building relative coordinate systems. This method is suitable for automatic pre-alignment of instruments with motorized stages, however, it can provide support also for manual alignment.

2. Automatic alignment system concept

The fiducial markers used in Augmented Reality applications hold an unique ID, a number between 1 and n (depending on how large the dictionary used is), which can be detected and retrieved from images using a processing algorithm (in a similar manner with bar-codes or QR-codes). In addition, their position and orientation with respect to the camera used for imaging can be estimated. This is achieved with the aid of the projective geometry which provides a pinhole camera model that is expressing the relationship between physical 3D points and their 2D projections from images [17].

For implementing the alignment method, ARUCO markers were chosen, given a complete software library with tools for generating and detecting the markers is available [18], [19]. In figure 1 is shown an ARUCO fiducial marker where the ID is detected by the library, while the position and orientation is estimated.

It is considered that the camera holds a virtual coordinate system having the z axis normal to the image sensor \((\vec{x}_c\vec{y}_c\vec{z}_c)\) - figure 1). The fiducial marker has a similar coordinate system attached \((\vec{x}_m\vec{y}_m\vec{z}_m)\). The ARUCO algorithm is estimating the position and the orientation of the marker coordinate system relative to the camera coordinate system. This is given by a homogeneous transformation denoted as \(T^{cm}\) (the transformation between the camera coordinate system and the marker coordinate system) which is defined as:
\[ T_{cm} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & x \\ r_{21} & r_{22} & r_{23} & y \\ r_{31} & r_{32} & r_{33} & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \] (1)

where \( R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \) is a rotation matrix which expresses the orientation of the \( x_m y_m z_m \) coordinate system relative to the orientation of the \( x_c y_c z_c \) coordinate system while \( x, y, z \) expresses their relative position.

Considering that \( x_c, y_c, z_c, x_m, y_m, z_m \) are versors (orthogonal unit vectors) it can be written that:

\[
\begin{align*}
    r_{11} &= x_m \cdot x_c \\
    r_{12} &= y_m \cdot x_c \\
    r_{13} &= z_m \cdot x_c \\
    r_{21} &= x_m \cdot y_c \\
    r_{22} &= y_m \cdot y_c \\
    r_{23} &= z_m \cdot y_c \\
    r_{31} &= x_m \cdot z_c \\
    r_{32} &= y_m \cdot z_c \\
    r_{33} &= z_m \cdot z_c
\end{align*}
\] (2)

where the operator "\( \cdot \)" denotes the dot product. Also, the two origins (\( O_c \) and \( O_m \)) are defining the following position vector:

\[ O_c \tilde{O}_m = x \cdot x_c + y \cdot y_c + z \cdot z_c \] (3)

Figure 1. The estimation of the position and orientation of an ARUCO [18], [19] fiducial marker and ID identification using an imaging camera. This is achieved using the pinhole camera model in which the extrinsic parameters are determined knowing the intrinsic ones [17].

In general, the experimental setups are positioned using absolute references which rely on precise features in the interaction chamber (ex. the target chamber center, metallic stalks or optical irises). In the case of solid targets, the positioning of the targetry equipment relative to another, like the alignment microscope, would be desired. In this approach of relative positioning, the target can be automatically pre-aligned without requiring to align the target.
Figure 2. Experimental setup example and pre-alignment system using fiducial markers. The experimental setup is composed by: interaction chamber (1), laser beam input flange (2), off-axis parabolic mirror (OAP) (3), OAP manipulator (4), optical microscope (5), microscope manipulator (6), target frames (7), target feeding system (8), target frame manipulator (9), detector (10), detector manipulator (11), imaging camera (12). The fiducial markers attached on each relevant instrument are drawn in blue.

to the laser beam. The laser focal spot is optimized and its position is determined using an alignment microscope which becomes the reference position for pre-aligning the target. This method allows also to automatically exchange the target from the manipulator using a target feeding system whose position and configuration was changed without the need of a calibration procedure. Moreover, it is possible to automatically position instruments with motorized stages in positions relative to the target frame or relative to another instrument.

In figure 2 is presented an example of experimental setup where the instruments are pre-aligned relative one to each other’s positions. The proposed method is used for rough alignment and coupled with the rear surface imaging method for fine alignment. It is considered that in the interaction chamber (1) all relevant instruments have attached on them a fiducial marker (drawn in blue), which are used to build relative reference positions. The experimental setup is composed by: laser beam input flange (2), off-axis parabolic mirror (OAP) (3), OAP manipulator (4), optical microscope (5), microscope manipulator (6), target frames (7), target feeding system (8), target frame manipulator (9), generic detector (10), detector manipulator (11), imaging camera (12). The camera used for imaging needs to be fixed before each instrument pre-alignment, but
it can be moved conveniently from one instrument to another especially when working in large interaction chambers.

**Figure 3.** Target pre-alignment in microscope’s field of view. The figure illustrates how the relative reference positions and virtual coordinate systems can be defined. The virtual coordinate systems considered are illustrated simplified through red circles accompanied by a set of letters for reference (c - the virtual coordinate system attached to the camera; mm - attached to the fiducial marker on the microscope; mf - attached to the center of the focal plane of the microscope; fm - attached to the fiducial marker on the frame; t - attached to the target). Between these coordinate systems are defined homogeneous transformations which partially are known a priori, and partially are determined in real time using the fiducial markers.

As a clarifying example, in figure 3 is presented an approach for considering and defining the virtual coordinate systems and the relative reference positions for pre-aligning the target in microscope’s field of view (FOV). This choice is not unique, the user has to build his own setup while deciding how to consider the virtual coordinate systems and where to place the fiducial markers, developing calibration procedures accordingly. The instruments are marked using the same numbers as in figure 2 while the markers are also drawn in blue. The virtual coordinate systems considered are illustrated simplified through red circles accompanied by a set of letters for reference (c - the virtual coordinate system attached to the camera; mm - attached to the fiducial marker on the microscope; mf - attached to the center of the focal plane of the microscope; fm - attached to the fiducial marker on the frame; t - attached to the target).

$T_{cm}$ defines the relative position and orientation between the camera coordinate system and the coordinate system attached to the fiducial marker on the microscope. The center of the focal plane of the microscope (MCFP) has a well defined position determined by the microscope’s construction (sensor and optical system characteristics). $T_{fmm}$ defines this relative position and orientation between the coordinate system attached to the fiducial marker on the microscope and the coordinate system attached to the center of the focal plane. This homogeneous transformation will remain unchanged as long as the microscope assembly is not
Table 1. The virtual coordinate systems and homogeneous transformations for target pre-alignment in microscope’s FOV.

| Virtual coordinate system A | Virtual coordinate system B | A to B transformation | Source |
|----------------------------|-----------------------------|-----------------------|--------|
| Camera                     | Microscope marker           | \( T^{mm}_{cm} \)     | Using ARUCO library |
| Microscope marker          | MCFP                        | \( T^{mf}_{cm} \)     | Manufacturing or calibration |
| Camera                     | MCFP                        | \( T_c^{mf} = T_c^{mm} \cdot T_{mm}^{mf} \) | Computed in real-time |
| Frame marker               | Target                      | \( T_{fm}^{t} \)      | Using ARUCO library |
| Camera marker              | Target                      | \( T_c^{t} = T_c^{fm} \cdot T_{fm}^{t} \) | Computed in real-time |

modified. It can be obtained either through precise design and manufacturing of the microscope, either through a calibration procedure using a dedicated calibration setup. Consequently, the relative position and orientation between the camera coordinate system and the coordinate system attached to the center of the focal plane is defined as:

\[
T^{mf}_{cm} = T^{mm}_{cm} \cdot T_{mm}^{mf}
\]  

For the target frame, \( T^{fm}_{c} \) defines the relative position and orientation between the camera coordinate system and the coordinate system attached to the fiducial marker on the frame. \( T^{t}_{fm} \) defines the relative position and orientation between the coordinate system attached to the fiducial marker on the frame and the coordinate system attached to the first target from the frame. This homogeneous transformation is determined by the frame construction and where the fiducial marker is placed and will remain unchanged as long as the frame or the target wafer structure is not altered. Consequently, the relative position and orientation between the camera coordinate system and the coordinate system attached to the first target from the frame is defined as:

\[
T^{t}_{c} = T^{fm}_{c} \cdot T^{t}_{fm}
\]  

The manner in which the coordinate systems and the homogeneous transformations are considered and defined is summarized in Table 1.

The target is pre-aligned in the microscope’s FOV when the two homogeneous transformations \( T^{mf}_{cm} \) and \( T^{t}_{c} \) are made equal by moving the motorized manipulators.

In the same manner, the OAP can be automatically pre-aligned whenever the focusing configuration is changed, in relative positions to the laser beam input flange.

For exchanging the target using the feeding system, the target manipulator needs to be placed in a precise position in order to ensure the interface between the two motion systems. The manipulator can be pre-aligned using two fiducial markers attached on the two instruments.

Typically, any type of detector that is moved using a motorized manipulator can be pre-aligned in a fixed position relative to the interaction point by using a fiducial marker attached on it and the one from the target frame.

3. Automatic alignment system prototype
The relative reference positions are build using fiducial markers attached on targets and instruments. In order to achieve the pre-alignment as described, by imposing the equality of two
homogeneous transformations, we developed an algorithm that iteratively searches the positions along all the stages from a manipulator until the equality condition is met. The algorithm runs in real-time and at its core it solves an optimization problem using the numerical gradient descent method [20] where the gradient is estimated in real time at each iteration [21].

In a previous work [22] the accuracy of measuring the position and orientation of an ARUCO fiducial marker was experimentally determined. By using a 140 µm optical resolution imaging setup, it was obtained a measurement accuracy along the X and Y axis of approximately 75 µm. Along the Z axis, the accuracy was about 300 µm.

In order to test the accuracy of the pre-alignment method and the positioning algorithm, we built a test setup, as sketched in figure 4. The core is an embedded computing module (Nvidia Jetson TX1) which runs the ARUCO library and the real-time positioning algorithm.

The manipulator has 5 degrees of freedom (3 translations, one rotation and one goniometer) and is assembled from vacuum compatible Standa stages having a resolution of 2.5 µm/step and 0.6 arcmin/step respectively. It is controlled using Standa controllers and a computer running a Tango server which receives commands from a Tango client running on the Jetson device. On top of the manipulator an ARUCO marker is attached. For imaging, a 2 Mpix camera with a 25 mm lens was used. The distance between the camera and the fiducial marker is around 80 cm.

This test is considering only the translation positioning and not the orientation. The test procedure follows the next steps:

(i) the manipulator is moved to a fixed, known position (X = 15000, Y = 20000, Z = 30000 steps)
(ii) the position and orientation of the fiducial marker ($T^m_c$) is stored and considered the reference position

![Figure 4. Pre-alignment system prototype setup. The core of the prototype is an embedded computing module, Nvidia Jetson TX1. It runs the ARUCO library for estimating the position and orientation of the fiducial marker, the Tango client that interacts with the motorized manipulator, the Basler Pylon library for controlling and acquiring images from the camera and the real-time optimization algorithm for driving the positioning.](image-url)
Table 2. Positioning accuracy results after tests. The quantities marked with * are given in motor steps.

| Test no. | Position after 7 iterations | Positioning error - manipulator |
|----------|----------------------------|-------------------------------|
|          | X* | Y* | Z* | ∆X* | ∆Y* | ∆Z* | ∆X[µm] | ∆Y[µm] | ∆Z[µm] |
| 1        | 14985 | 20008 | 30022 | +15 | -8 | -22 | +37.5 | -20 | -55 |
| 2        | 14993 | 19996 | 29965 | +7 | +4 | +35 | +17.5 | +10 | +87.5 |
| 3        | 14977 | 20000 | 29938 | +23 | 0 | +62 | +57.5 | 0 | +155 |
| 4        | 15018 | 20004 | 30070 | -18 | -4 | -70 | -45 | -10 | -175 |
| 5        | 15004 | 19998 | 30007 | -4 | +2 | +26 | +57.5 | 0 | +155 |

(iii) the manipulator is moved to its home position (X = 0, Y = 0, Z = 0 steps)
(iv) the real-time positioning algorithm is started. It needs to bring back the fiducial marker to the reference position without knowing that this corresponds to X = 15000, Y = 20000, Z = 30000 steps in manipulator coordinates

Five tests were made in order to prove the consistency of the results. For each test, the positioning algorithm ran for 7 iterations. The results are presented in table 2.

The results of the tests show that the positioning error along the X and Y axis is less than 60 µm, while along the Z axis is higher, at around 180 µm. This is consistent with the precision of measuring the position of the fiducial markers which along the Z axis is lower compared with the X and Y axis. Each positioning test lasts less than 4 minutes and after the first iteration the positioning error was less than 1 mm.

4. Conclusions
The pre-alignment method revealed during the first tests an accuracy between 100-200 µm, achieved using only a 2 Mpix camera. Although the method was conceived to be used as an automatic pre-alignment phase in addition to another fine alignment method (ex. rear surface imaging), it can be further improved and used as stand-alone for applications where an accuracy of few tens of microns is enough.

The accuracy of the method is directly influenced by the accuracy in detecting the position and the orientation of a fiducial marker. A detailed study on this topic can be found in [22]. The accuracy scales linearly with the resolution of the imaging camera. Using, for example, a 10 Mpix camera in a similar setup can lead to a theoretical accuracy of up to 20 µm. Furthermore, using different imaging camera optics can improve the results with the cost of reducing the working volume.

The optimization algorithm is also responsible for how accurate the method is. At the current stage of development, the optimization method based on gradient descent was implemented in a standard approach. Multiple improvements are envisaged for tuning in real-time the gradient which will increase the convergence, therefore, the alignment will be faster and more accurate.

Future works will focus also on extending the algorithm in using multi-camera setups in order to improve the accuracy along the Z axis and for expanding the working volume. For mitigating the effect of illumination on the accuracy, automatic camera calibration algorithms are also required to be developed.

Acknowledgments
This work is supported by Extreme Light Infrastructure Nuclear Physics (ELI-NP) - Phase II, a project co-financed by the European Union through the European Regional Development
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