FINAL CONCEPT OF THE PHOTOGRAMMETRIC ALIGNMENT SYSTEM RALF FOR HIGH-RADIATION AREAS OF FAIR

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Abstract

At IWAA 2006 we presented the preliminary concept of a new alignment system, designed for the use in inaccessible, high-radiation areas of the future "Facility for Antiproton and Ion Research" (FAIR) at GSI. The alignment system RALF – **R**emote **Al**ignment on the **F**ly – is based on a photogrammetric approach. This will ensure a remote-controlled, accurate and fast measurement process.

The final project phase consisted of validation and optimization of the concept by means of practical investigation on a test site using a RALF prototype. Besides investigations of the measurement configuration also practical aspects like type and size of targets or illumination influence have been studied. The results of the test installation confirmed the theoretical concept and therefore put the final concept on a reliable basis.

INTRODUCTION

At the past IWAA's we introduced both the new accelerator facility FAIR [1], which is planned to be built next to the existing GSI laboratory (Gesellschaft für Schwerionenforschung), and the intermediate concepts for the survey and alignment system RALF [2] [3].

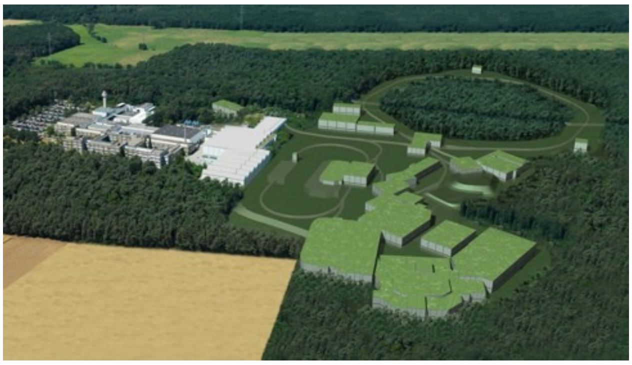

Figure 1: Aerial view of GSI with photo composition showing FAIR

In the meantime the FAIR project moved forward to the next level: On November 7, 2007, representatives of the partner countries, representatives of German Government and the partner countries announced the go-ahead for construction of the accelerator facility FAIR. The construction work is due to start in the winter of 2008/09, with the project to be completed by 2015/16 [4].

Moreover, in August 2007 the authors of this manuscript finished their conceptional work concerning the new survey and alignment system for specific parts of FAIR. The project RALF was initiated in 2004 in order to lay the foundations for an accurate alignment of accelerator components, which is important for the ion-optical resolution and transmission at FAIR. The results of this work will be presented in this paper

MOTIVATION AND OBJECTIVES

In some areas of FAIR the survey and alignment group will have to face serious constraints. In several locations of the future facility FAIR a high level of neutron production and activation can be expected such a kind, that – even in periods the accelerator is switched off – personnel will be exposed to a radiation dose which exceeds the permissible dose rate around a multiple, due to the activation of the tunnel walls and accelerator components. This will be true particularly in the areas of the superconducting fragment separator (Super-FRS). These areas are expected to remain inaccessible for personnel even for usual shutdown service activities, once initial installation and commissioning are completed. Concerning future survey and realignment tasks these circumstances prohibit the use of well-established stationary monitoring systems or classic measurement systems like total station or laser tracker. The basic necessity for using automated, remote systems for position control and realignment within these zones is therefore obvious.

The new measurement system has to meet the following requirements:

- No access of human personnel
- Required accuracy of about 1/10 mm
- Fast data acquisition
- Automated, remotely controlled adjustment of Super-FRS components
- Handling a non-linear beam line with a length of several decameter

The method will not be used as a permanent monitoring system but for regular determination of the actual condition of the machine geometry. The measurement method shall be based on the principle of photogrammetry, as this appears to be the most applicable technique for this purpose. Commonly used remote alignment methods like WPS, TMS or HLS appear to be inapplicable, or at least very expensive, considering the enormous radiation level and the non-linear, stretched geometry.

While the configuration of RALF will be adapted on the environmental conditions of the Super-FRS, it is, however, considered to be applicable for other accelerator areas as well, e.g. anti proton target or SIS.

THE CONCEPT OF RALF

As introduced at IWAA'06, RALF is based on two remote-controlled vehicle systems, which will be driven along the accelerator tunnel. Four high-precision digital cameras mounted on these vehicles are designated to capture images of the machine geometry, represented by appropriate targets. Provided that the fiducial coordinates of the targets are assigned to the magnet geometry prior to the alignment, a bundle block adjustment of the image measurements of the targets delivers precise 3D information of the beam line. A comparison to the nominal results in correction values for the alignment of the accelerator components that is completed by using remotely controlled positioning elements.

Due to radiation protection measures all maintenance work – including the alignment – has to be carried out on the service platform above the beam line. Therefore the fiducials (resp. their supports) have to be extended to the outside of the shielding. This is intended by installing up to two meter long, very stable rods, pulled through holes in the iron blocks and mounted onto the magnet yoke (cf. Fig. 2). Of course, sufficient reliability and reproducibility of this construction is a basic necessity, and will be subject of further investigations.

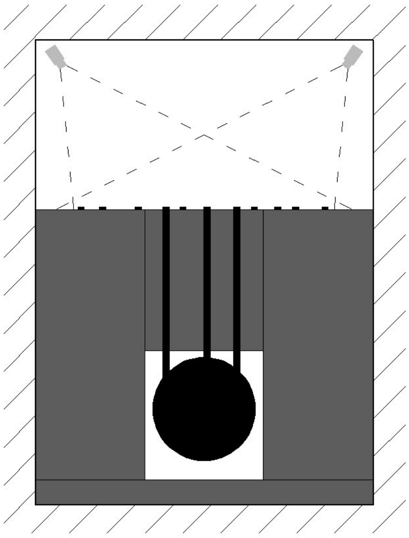

Figure 2:. Schematic layout of the heavy shielded areas of the Super-FRS. Shieldings are painted in gray. Three rods are illustrated, which transfer the machine geometry to the service platform. Additional photogrammetric tie points are placed on the ground of the platform

According to the simulation results, the configuration of RALF will look as follows: Two camera vehicles, each equipped with two cameras, will move along the tunnel at a height of 1,30 m and take pictures at regular intervals. Thus each photogrammetric target is defined by at least four image rays, which should provide enough redundancy to compensate temporary losses of image measurements due to interferences like hidden targets or erroneous target identification and image measurements.

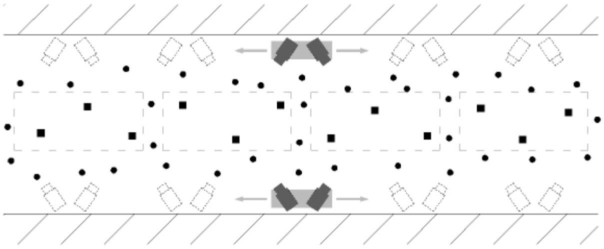

Figure 3: Schematic top view of the working platform. Two camera vehicles, each equipped with two cameras, will move along the tunnel and take pictures at regular intervals. Excentric fiducial points are printed as squares, photogrammetric tie-points are printed as circles

PRACTICAL ASPECTS

In addition to extensive simulations in order to determine an appropriate configuration of RALF, the three-year project included some more tasks. The work on geometric camera tests and radiation tests of image sensors has been already presented at IWAA06. The remaining subtasks, their main results and some practical aspects will be described in the following.

Image analysis

Modern image processing techniques allow an automatic measurement of circular targets with sub-pixel accuracy. While a manual measurement of well-recognizable object features is possible with an accuracy of about 1/5 pixel, automatic methods have an accuracy potential of 1/20 to 1/50 pixel, depending on technique, image quality and on the types of targets [5]. Four different methods can be distinguished:

- Center of gravity (COG)
- Template matching
- Least squares Matching (LSM)
- Structural method based on an ellipse operator

In the past years LSM has established as an universal image measurement method and is therefore very well documented. The accuracy potential of this method is about 1/50 pixel (under ideal conditions) while approximately 1,000 points per second can be measured.

At i3mainz a software library was developed which can detect and measure both coded and uncoded circular targets in images based on the COG method [6]. However, this procedure proved to be rather slow, inflexible and inaccurate, compared to commercial products. Therefore ImetricS, a professional photogrammetric software for image measurement and bundle adjustment was used for all tests in the course of this project. ImetricS uses LSM for the measurement of the targets. As the tests have shown, the center points of the targets can be measured with an accuracy of 1/30 pixel using an AVT Pike camera (0.25 µm on the CCD sensor). Assuming a 16 mm lens and an average object distance of 3.2 meters, this translates to 0.05 mm at the object (image scale 1:200).

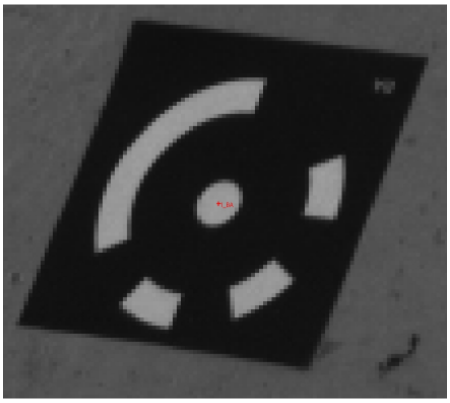

Figure 4: Automatic detection and sub-pixel localization of a circular target. In this case, the point ID ("I_BA") is automatically identified by analyzing the bar code circle. The target center can be determined with a precision of 1/30 pixel.

Transfer of accelerator geometry to service platform

As already mentioned above a solution has to be found to transfer the geometry of the accelerator components to the service platform. It is still under discussion how to solve this in detail. Several solutions are conceivable and have to be examined in discussion with the GSI radiation safety department. One of the ideas is shown in Figure 5.

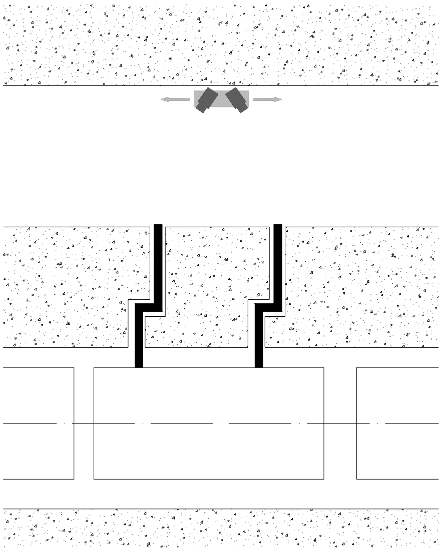

Figure 5: Schematic layout of a possible solution for transferring the magnet geometry to the service platform.

Due to safety reasons a straight and vertical gap in the shielding will probably not be possible. Therefore it might be an option to construct a non-linear gap in the shielding and use stable rods formed in the same way without touching the shielding. A second possibility would be to use straight, vertical gaps and rods, respectively, but remove the rods after each alignment and fill the holes in the shielding with suitable concrete columns. Very stable clutches would be needed at the magnets with very high repeat accuracy for the mounting of the rods.

Moving the accelerator components

At the existing accelerator facilities the magnets are aligned using mechanical machine mounts. In a rather "straightforward" manner a magnet can be moved and tilted in all directions using a screw-wrench at any of the four mounts. This demands a manual interaction of an engineer, which will not be possible at the Super-FRS.

Considering the fact, that the conditions at Super-FRS will be at some orders of magnitude worse than at other accelerator facilities (up to 14 MGy/year, 80 to 100 tons per magnet) it seems unlikely that a development of motorized jacks will be possible for the (target area of the) Super-FRS, at least unless a huge effort of R&D manpower and cost is made. Same applies to a hydraulic solution.

Therefore the most suitable solution appears to be a mechanical one. As mechanical machine mounts proved itself reliable and advantageous in the present accelerator facility, a future application of mechanical jacks at FAIR should be the first choice. But, instead of manual interaction using screw wrenches a motorized solution must be found. Using a combination of gearboxes and rodding will allow for a power transmission from the electronic stepper motors, located behind the shielding, to the machine mounts. For this purpose a use of standard components is conceivable.

Camera vehicle and motion system

A solution for the motorized camera vehicles can be realized using standard components as well. Several companies offer linear motion and drive systems in modular conception. Exemplarily, *Hepco* provided a quote including linear and circular components for two 30-meter-sections, two vehicles and aluminum profiles for wall mounting for a price of 17k€ (as at December 2006). The motors must be purchased separately. The advantage of this type of solution is the required space, which is low compared to a system driving on the floor (e.g. a robot carrying the cameras and following a white line painted on the floor).

Data transfer and power supply

The cameras, which are planned for RALF and which were used for the test installation, do not possess a storage medium. In order to be able to save the images and to control the cameras during operation, a cable connection must be established between cameras and computer. The Allied Vision Pike cameras have the possibility for using firewire interface or optical fiber cables. While the length of specified firewire connections is limited, the latter is suitable for cable lengths up to 500 m. A second advantage of fiber cables is their immunity to electromagnetic interference. Therefore fiber cables provide the best solution for data transfer and camera control. Standard E-chain cable carriers can be used to protect the data and power cables against physical damage.

Connection to adjacent sections of the Super-FRS

While a solution was found for the alignment process on the service platform, it is not yet clear how to manage the metrological connection to the adjacent sections of the Super-FRS. This strongly depends on the specifications of the radiation safety department. In any case it will be necessary to establish intervisibility between accessible and non-accessible areas. The cameras of RALF must be able to observe targets in the adjacent sections in order to connect both parts of the accelerator and to guarantee a correct, smooth beamline.

Since the magnets in the accessible parts of FAIR will be aligned using the conventional methods, targets must be used which are suited to be measured both by the TASA system (tacheometer, laser tracker) and by photogrammetry (cf. Fig. 6).

Figure 6: Special target for photogrammetric measurements, which can be replaced by laser tracker targets, using the respective sphere mounts.

TEST INSTALLATION

As presented at IWAA'06 the simulations showed that the accuracy potential of RALF can be expected at 0.1 mm and below. After these theoretical investigations were finished, it was planned to build up a test installation of RALF, in order to

- verify the simulations
- test the cameras practically
- test different types of targets and image analysis
- investigate the influence of different configurations of the bundle adjustment
- run exemplarily through a complete alignment process

In the following chapters the setup and the results of the test installation will be presented.

Setup

Since it was not allowed to build up a test site at a section of the present accelerator, a rarely frequented supply corridor was chosen on the third floor of the GSI main building. With a width of 4.2 meters the corridor provided conditions similar to the future service platform at Super-FRS. Except for some pipes on one wall and on the ceiling, the corridor was completely deserted over a length of more than 20 meters. Illumination consisted of a single line of fluorescent tubes and windows at intervals of 10 meters. However, the windows have been darkened for most of the tests due to strong lighting variations in the images. Also tests with movable spotlights were carried out instead of the ceiling light, but results were rather poor. In contrast, the nearly diffuse illumination provided by the fluorescent tubes yielded evenly illuminated images, independent of camera position.

Two Pike 421B cameras by Allied Vision were purchased for the test installation together with two 16-mm lenses. The cameras were installed on an aluminum plate (Figure 7), which itself was mounted to a three-way head on a heavy tripod. The tripod was moved manually along the corridor, simulating what in future will be done automatically using a linear motion system. The cameras were connected to a laptop computer, which was used for controlling the camera parameters (mainly exposure time), shooting the images and saving them on hard disk for later processing.

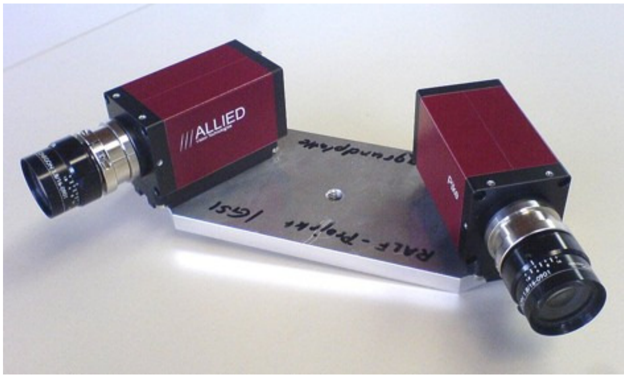

Figure 7: Two Pike cameras mounted on the aluminum plate

Figure 8: Test installation. On the right hand side the two cameras are mounted at 130 cm height on a tripod. Coded and uncoded targets as well as six scale bars are placed on the floor. In the center part the table can be seen which is used to simulate a misaligned magnet.

A 12 m section of the corridor floor was chosen in order to simulate the future alignment on the service platform. About 60 coded and 150 uncoded targets were sticked randomly on a 2 m by 12 m area in the middle of the floor. In addition six calibrated scale bars were distributed on the floor, providing the basis for scaling the object coordinates and checking the accuracy of the measurement system.

For the simulation of a misaligned magnet a small table was equipped with targets and placed in the middle of the observed section. Four machine mounts were used to displace the table deliberately between two measurement epochs. Six mechanical dial indicators with a resolution of 0.01 mm were mounted on the table in order to control and check the displacement of the table with high accuracy.

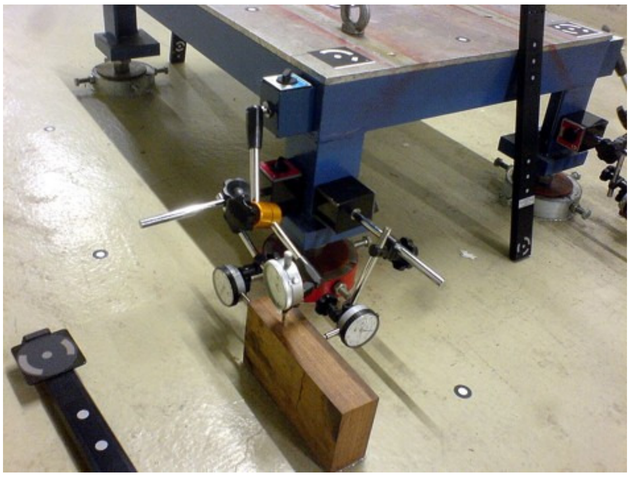

Figure 9: Table with machine mounts and dial indicators, used for a controlled misalignment.

Workflow

Prior to all measurement tasks at the test installation the cameras, focused to the specific object distance, have been calibrated using an on-site test field which mainly consists of the table and its surrounding floor, equipped with targets, and some scale bars distributed around the scene.

In order to verify the performance of RALF, the following steps have been taken:

1. *Shooting of the photos*. A total of 52 images were taken at 1 m intervals (13 positions x 2 images on each side of the corridor)

2. *Automatic image analysis and bundle adjustment*. Commercial software ImetricS (image measurement) and Ax.Ori (bundle adjustment) have been used for this purpose. The adjustment results in local coordinates of all targets.

3. *"Misalignment" of the table.* The table was moved in three directions according to Figure 10. The readings of the dial indicators were converted to XYZ correction values for each single target point on the table.

4. *Second measurement run*. Repetition of steps 1 and 2

5. *Determination of misalignment*. The two lists of coordinates are now transformed into the same coordinate system using a spatial 6-parameter transformation. After that the coordinate differences between the two measurement runs (before and after the misalignment) can be calculated.

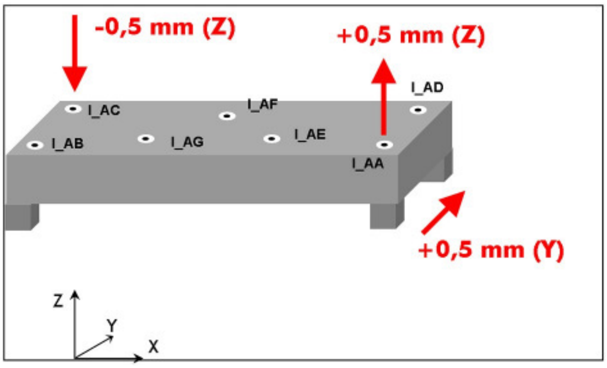

Figure 10: Movement of the table prior to the second measurement

Results

In the following table some results of the bundle adjustments are shown.

Table 1: Bundle quality check of the two measurement epochs. The accuracy potential of this system is below 0.1 mm for a single point.

[mm]	Run 1	Run 1 with fixed camera pairs	Run 2	Run 2 with fixed camera pairs
RMS X std. dev.	0.043	0.031	0.041	0.030
RMS Y std. dev.	0.044	0.034	0.041	0.033
RMS Z std. dev.	0.049	0.038	0.045	0.036
RMS 3D point	0.079	0.060	0.073	0.057
RMS dist. differences	0.119	0.069	0.084	0.061
MAX dist. difference	0.182	0.109	0.146	0.104

At first the whole image bundle was used for the calculations, with 52 independent exterior orientations for the 52 images (columns 1 and 3). In a second run only half of the exterior orientations have been calculated (only the "left" images), while a constant relative orientation was assumed, linking left and right image from the same observation point (columns 2 and 4). As can be see in the result table, this procedure leads to an accuracy improvement of about 30%.

In order to evaluate the repeat accuracy of the system, the object coordinates have been transformed into the same coordinate system, without using the targets on the movable table. Table 3 shows the RMS and maximum values of the differences between the coordinates. The average differences in all coordinate directions are well below 0.1 mm.

Table 2: Displacement values of the table targets, determined both with dial indicators and RALF. The three columnson the right hand side show the difference between target and actual misalignment.

	Displacement (from dial indicators)			Displacement measured with RALF			Difference		
[mm]	X	Y	Z	X	Y	Z	diff X	diff Y	diff Z
I_AA	0.08	0.54	0.31	0.06	0.59	0.37	0.02	-0.06	-0.06
I_AB	0.08	0.22	0.00	0.02	0.19	-0.06	0.06	0.03	0.06
I_AC	-0.12	0.22	-0.27	-0.18	0.24	-0.32	0.06	-0.02	0.04
I_AD	-0.12	0.54	0.05	-0.19	0.64	-0.16	0.07	-0.10	0.21
I_AE	0.01	0.44	0.13	-0.08	0.48	-0.02	0.10	-0.03	0.14
I_AF	-0.10	0.38	-0.09	-0.17	0.39	-0.04	0.06	-0.01	-0.04
I_AG	0.01	0.29	-0.03	-0.01	0.32	-0.18	0.03	-0.04	0.15
RMS							**0.06**	**0.05**	**0.12**

Table 3: Comparison of the object coordinates of the two measurement epochs after transformation (repeat accuracy)

[mm]	**X**	**Y**	**Z**	**3D**
RMS	0.03	0.02	0.06	0.07
Max.	0.07	0.09	0.15	0.19

Finally the absolute displacement of the table was calculated and compared to the expected values, measured with the help of the dial indicators. In Table 2 the results are displayed.

Considering that the reference measurement of the displacement using the dial indicators is only of limited accuracy and reliability, the results of the RALF measurement look excellent. The misalignment of the table could be clearly detected while the measurement accuracy of a single point is around 0.1 mm. With the help of the resulting accuracy of the target points now the final correction values for adjusting the machine mounts can be calculated.

CONCLUSION

In this paper the work has been described, which lead to the concept of a remote-controlled alignment system for the future Super-FRS of FAIR. The system will consist of two motorized vehicles, each equipped with two 4 mega pixel cameras. The alignment system called RALF will be able to achieve a single point accuracy of below 0.1 mm, which was confirmed by both simulations and practical investigations on a test installation. Additional investigations have been carried out in order to define the special constraints on the accelerator design and the concept of RALF.

However, during the course of this project it became obvious, that the crux of the problem will not be the metrological side but rather several practical aspects and constraints on the future accelerator facility. Most of them are not finally solved yet and require more discussion between several departments (civil construction, radiation protection, metrology, beam physicists, …). The most important issues are outlined in the following:

- radiation-protected storage room for cameras
- illumination of the service platform
- transfer of accelerator geometry to service platform
- machine mounts for remote adjustment
- installation of a linear motion system
- connection of service platform to adjacent sections

Nonetheless the concept of RALF is a promising alternative to traditional alignment methods, as it is applicable at many accelerator areas, not only at the Super-FRS.

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