ISSUES AND FEASIBILITY DEMONSTRATION OF POSITIONING CLOSED LOOP CONTROL FOR THE CLIC SUPPORTING SYSTEM USING A TEST MOCK-UP WITH FIVE DEGREES OF FREEDOM

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Abstract

Since several years, CERN is studying the feasibility of building a high energy e+ e- linear collider: the CLIC (Compact LInear Collider). One of the challenges of such a collider is the pre-alignment precision and accuracy requirement on the transverse positions of the linac components, which is typically 14 µm over a window of 200 m. To ensure the possibility of positioning within such tight constraints, CERN Beams Department's Survey team has worked intensively at developing the methods and technology needed to achieve that objective. This paper describes activities which were performed on a test bench (mock-up) with five degrees of freedom (DOF) for the qualification of control algorithms for the CLIC supporting system active-pre-alignment.

Present understanding, lessons learned ("know how"), issues of sensors noise and mechanical components nonlinearities are presented.

INTRODUCTION

The most critical CLIC RF components need to be pre-aligned within 14 µm rms with respect to a straight reference line along a sliding window of 200 m [1].

A system based on supporting structures (girders and cradles) connected in "snake"-type configuration and equipped with linear actuators is being tested. A special test mock-up was built at CERN (Figure 1) to demonstrate, inter alia, the feasibility of remote active pre-alignment within tight tolerances. To achieve the requirements, all main parts of the CLIC mock-up were machined with high precision and measured to determine the position of the reference axis/zero of the component with respect to external alignment references called fiducials - fiducialisation process [2].

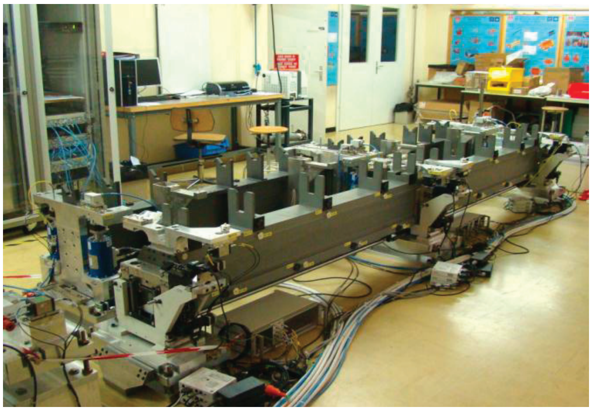

Figure 1. Test module mock-up

Linear actuators were qualified on a 1 DOF test-bench, with a resulting repeatability below 1 µm measured along their whole range.

The mock-up was equipped with high precision Wire Positioning Sensors (WPS) and inclinometers – giving feedback data to compute the position of supporting structures w.r.t reference coordinate system (linked to stretched wire). All tests were performed under control of specially designed software to examine the system behaviour during repositioning and verify operation of pre-alignment control algorithms.

ACTIVE PRE-ALIGNMENT USING LINEAR ACTUATORS IN "SNAKE"-TYPE GIRDERS CONFIGURATION

All CLIC RF components will be installed on modular girders (rigid part of length 2.01 m), which will be used as a support for RF components pre-alignment. Because several thousands of girders are needed for CLIC, the amount of components used (sensors and actuators) should be substantially decreased. One of the solutions is to install motorization only at one side of a girder (MASTER cradle) and leave the non-motorized side (SLAVE cradle) to be driven by the adjacent girder as shown in Figure 2. This solution smooths out "naturally" the pre-alignment of adjacent girders.

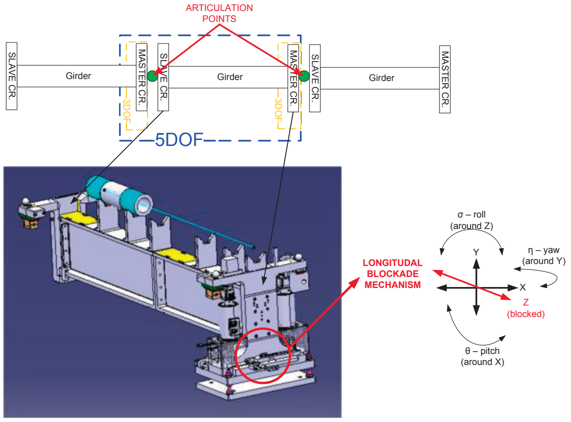

Figure 2. "Snake"-type girders configuration

Only the MASTER cradle has impact on the active pre-alignment process. Figure 3 shows its operating principle, the coordinate system and the angular motions. The cradle is suspended on two vertical actuators and is connected with one radial actuator. The actuators control the X-Y position as well as the roll of a cradle resulting in a 3 DOF mechanism. Connecting joints are elastic in direction transversal to actuator axes but rigid longitudinally, thus giving stiffness to the cradle suspension and enabling required motions.

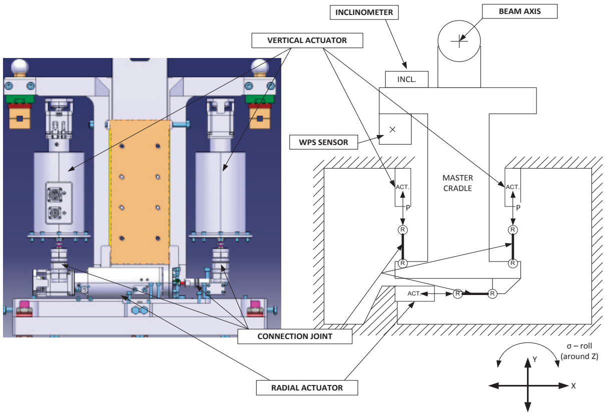

Figure 3. Master cradle schema – 3 DOF mechanism

Because longitudinal motion is blocked mechanically at the MASTER side (Figure 2), a combination of cradles MASTER-SLAVE-MASTER allows girder position control in 5 DOF.

MASTER-SLAVE connection quality plays a very important role in the “snake” type girder configuration. According to budget of alignment errors [1] – the interconnection offset error after pre-alignment should be lower than 10 µm rms.

The position of the common axis of the RF components mounted on the girder will be given by one WPS and one inclinometer feedback signals (both located on the MASTER cradle) computed with data coming from fiducialisation process [2]. Currently whole sensors are not ready to provide absolute reference values.

The whole “snake” structure can be pre-aligned by setting the beam axis positions of all MASTER cradles in one line w.r.t. reference coordinates coming from the tunnel coordinate system which shall be an external and independent reference for components alignment.

MASTER CRADLE KINEMATICS AND CONTROL ALGORITHMS

Theoretical approach to cradle kinematics

Because the longitudinal (Z-direction) movement of MASTER cradles is blocked (Figure 2), the 3 DOF MASTER cradle, equipped with linear actuators, can be considered as an object in 2D space. It forms a triple, parallel P-R-R (prismatic-rotation-rotation) kinematics circuit (Figure 4). This configuration can be described as simplified 2D **-** 3 supports- Stewart Platform with Fixed Actuators (SPFA).

Standard approach to parallel mechanisms regulation is to prepare equations of the platform based on the vectors which define kinematics chain nodes. Inverse kinematics then gives the wanted actuator lengths to reach requested platform orientation. Forward kinematics of the cradle can be calculated using Newton’s method.

In MASTER cradle case the vertices of the platform are defined by cradle vectors ($\mathbf{p}_i^C$) and base coordinates ($\mathbf{b}_i^B$, $\mathbf{h}_i^B$, $\mathbf{l}_i^B$). The platform is supported by joints (links) of constant length $\mathbf{l}_i$, and the joints are attached to the actuators of variable height $\mathbf{h}_i$, (Figure 4).

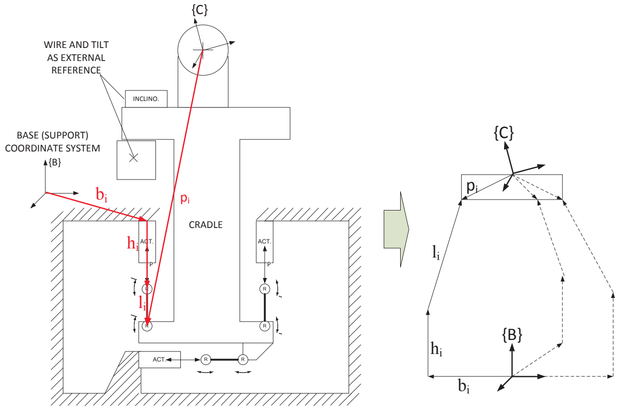

Figure 4. MASTER cradle as prismatic-rotation-rotation kinematics circuit and its vector representation

The described model approach can be correct only if we consider that all vectors are well known. Some inaccuracies of vectors dimensions will result of errors during alignment. The biggest source of errors can be vectors $\mathbf{b}_i$ and $\mathbf{l}_i$. Vector $\mathbf{b}_i$ describes the position of the i^{th} actuator w.r.t. {**B**} (base/reference coordinate system). However, it will be impossible to link the actuator support coordinate system “rigidly” w.r.t. tunnel coordinate system in the CLIC design because of machining errors of actuator supports, settling errors of supporting plates and local ground motions. Vector $\mathbf{l}_i$ describes joints which are elastic transversally to the actuator axis and shall be rigid along actuator axis, but in reality $\mathbf{l}_i$ can change length during the displacement of the mass of the girder and of the installed components (girder centre-of-gravity displacement).

Practical issues of cradle kinematics

From the kinematic chain point of view, the girder and cradles parameters are verified and stable at known temperature (dimensions are controlled during the fiducialisation process, the construction is rigid and the coordinates of the sensors are well known w.r.t. beam line and reference surfaces).

To be free of suspension components constraints (defined above) – the closed control loop method was chosen for active pre-alignment.

Approximate relative movements of each actuator ($\Delta\mathbf{h}_{i\_vertical}$, $\Delta\mathbf{h}_{i\_radial}$) to reach required girder position can be calculated using shift error vectors. These vectors are based on sensor feedback data, on requested RF components axis position and on fiducialised cradles/girder geometry (Figure 5). Vector ${}^{B}\mathbf{p}_i$ defines the current position of i^{th} cradle suspension node in {**B**} and vector ${}^{B}\mathbf{p}_i'$ presents the requested position of the same node in {**B**}. Shift error vector for each suspension node is then ${}^{B}\mathbf{e}_i = {}^{B}\mathbf{p}_i' - {}^{B}\mathbf{p}_i$.

The vertical actuators have small influence in the cradle’s radial position (1 mm actuator shift causes the

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cradle radial movement of approximately 10 µm). Likewise, the radial actuators have small influence in the cradle's vertical position. Therefore, the inverse kinematics calculations can be simplified (cf. eq.1).

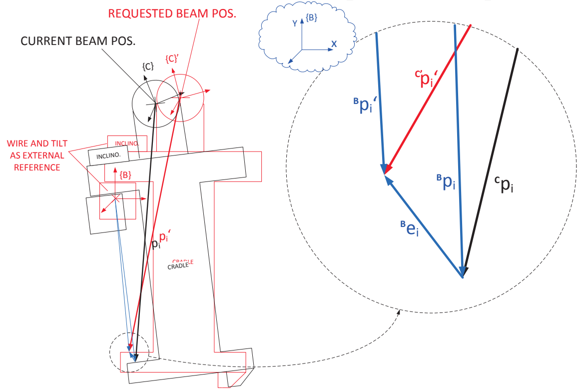

Figure 5. Shift error vector representation

$$e_{\mathbf{i}} = \begin{bmatrix} x_i \\ y_i \end{bmatrix}, \qquad \begin{aligned} \Delta h_{i\_vertical} &= f(e_{\mathbf{i}}) = y_i \\ \Delta h_{i\_radial} &= f(e_{\mathbf{i}}) = x_i \end{aligned} \qquad (1)$$

Embedding the above method in closed control loop gives iterative and convergent algorithm to pre-align a single cradle.

TESTS RESULTS

All tests were performed in the Test Module facility at CERN with single MASTER cradle. The external reference was a stretched wire. Random angle and position in accessible regulation space was chosen as reference "0".

Cycle time for closed-loop control algorithm was 4.5 s (change of position every 3 x 1.5 s data acquisition cycle to allow actuators to finalize shifts). The implemented algorithm is proportional. Therefore, no dynamic components are needed and the supporting structure is stable after the actuators are stopped. WPS sensor noise was at the level of 5 $\mu m_{p\text{-}p}$ and inclinometer noise was 5 $\mu rad_{p\text{-}p}$[3].

Two types of tests were performed: single step response and trajectory following. Figure 6 shows the step response with a requested relative shift of [-0.1, -0.1] mm.

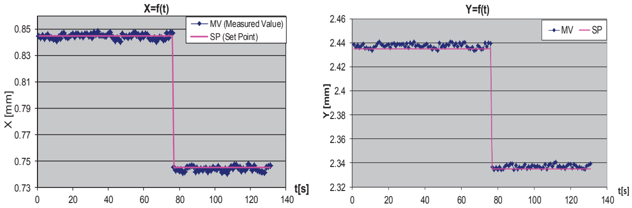

Figure 6. Single step response for the cradle position

Several tests with different step responses showed that the algorithm is convergent in maximum 2 regulation cycles for shifts lower than [+/-0.5 mm +/-0.5 mm]. A maximum of 4 regulation cycles is needed for bigger shifts.

Figure 7 shows trajectory following test. List of SP (Set Point) coordinates was requested sequentially, forming requested trajectory as "CLIC" caption patch. Single steps sizes were at the level of ~10 µm. Results (MV – Measured Value) show that regulation algorithm meets the requirements. Measured beam position value reaches destination and keeps SP within sensor noise.

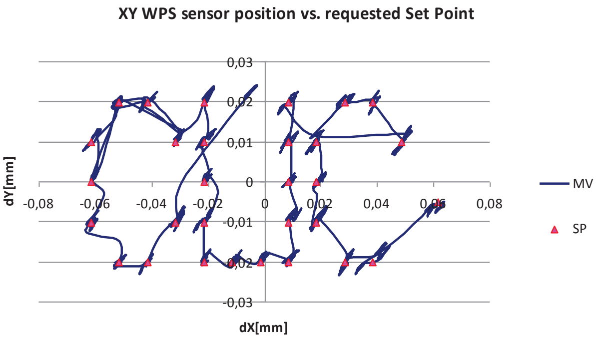

Figure 7. Trajectory following test results

Sensor tests were also performed [3]. Their noise was a problem - with level 4 to 5 times larger than required accuracy. A possible solution is statistical averaging of the sensors signals in time. Repeatability measured with 10 samples signal data averaging was at the level of 1 µm for the WPS and 1 µrad for the inclinometer. Because pre-alignment process has not narrow time constraints, we can use sensor data averaging in control loop (planned to be tested).

The determination of inclinometers absolute angle w.r.t cradle coordinate system represents a big challenge. With the most accurate measuring machine the obtained accuracy can't meet requirements: the inclinometer interface plate is too short. Intensive development is required to solve this problem.

CONCLUSIONS

Closed loop regulation – now only for relative displacements – shows that active adjustment of cradles is feasible within specified accuracy. All tests show that using cradle/girder geometry together with fiducialisation data to calculate actuators response gives promising results. Thanks to sensors feedback in regulation loop, all untrusted constraints (ground moves, components machining errors, etc.) influence can be eliminated. Sensors noise also affects the final regulation quality – the tests with signal processing will be performed to further improve the overall performance.

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