Cyber- Physical Systems Application for the Radio Telescope's Adaptive Surface Control Task

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ABSTRACT

In the paper cyber-physical systems' building conception is considered for industrial control plant that is represented by the adaptive surface radio telescope which consists of four moving mirrors, five fixed mirrors and a video camera. The mirrors are controlled by stepping motors. The laser rays' sources are used for the radio telescope's testing and video camera is used for getting of laser rays' positions. The cyber-physical system's architecture is developed on the base of containing elements' decentralized interaction using the PROFINET protocol. A problem of the radio telescope mirrors positions' tuning is formulated. The formula connecting the first mirror's slope and an incident angle is given, that is necessary for double reflected laser rays gathering within small adjustment area for further positioning. An accuracy criterion is chosen. An algorithm of laser rays and their control stepping motors matching is developed and shown in this paper. This algorithm's testing is also implemented. A next task is formulated based on necessity of a distance between laser rays and a center of adjustment area minimization.

1 INTRODUCTION

Technological expediency, operational necessity and economic efficiency allowed wide spreading of industrial automation. The automation has passed several historical periods in the course of its development.

Modern control systems are characterized by maximal reaction time for a fast changing environment, so high computation powers are needed for such systems. From that point of view usages of cloud computing might be a better solution comparing to traditional centralized system. Such architecture is able to simplify the control process of the whole system and introduce linear growth of the computational performance. Modern ideas of automation are based on Cyber-physical systems (CPS), which are used as intellectual control systems for improvement of control efficiency for kinds of complex object [3]. Fully steerable radio telescopes with the millimeter and submillimeter range and with a main reflector of up to 100 m diameter can be a good example [1,4,5,6,8]. One of actual problems for such systems is an observed radiation reception's level stabilization task under conditions of strong deformation because of gravity, temperature difference, wind and other environmental conditions. The form of a main reflector consists of several reflective screens that can be kept in necessary state by controlling every dimensional position of all system elements. The article bellow describes the control systems of a radio telescope with adaptive controlled reflector.

Consider the architecture of CPS first.

2 CYBER-PHYSICAL SYSTEM'S ARCHITECTURE

There are several features of CPS:

- CPS belong to the class of embedded systems, but they are more integrated into the control object;
- CPS based on the interaction of embedded systems and network technologies;
- CPS assume real-time interaction organization between processing units, actors and input/output devices
- systems have a decentralized control, i.e. the possibility of representing functional units of a system with autonomous devices, which leads to increased system flexibility;
- the ability to process unstructured data from various sources in real time;
- asynchronous operation of functional units of the system [7].

Information about the state of the control object comes from a large number of electronic devices, sometimes in an unstructured way. It should be clear that a key problem is synchronization of the received information for which it is necessary to use two-way data transmission system (wireless sensor network, wired network, etc.). A programmable logic controller (PLC) can be used as a processing unit for such systems, implementing system's functional logic. The control action involves precomputing (or information processing in accordance with a given algorithm) based on data received from sensors. In case of processing data from complex systems such as computer vision, it's important to provide high calculating performance, because otherwise the reaction time can be too long.

3 CYBER-PHYSICAL SYSTEM'S ARCHITECTURE

In the Peter the Great St. Petersburg Polytechnic University in Saint Petersburg the stand for complex surfaces control task's solving is being developed [2]. This stand is shown at *Fig. 1.*

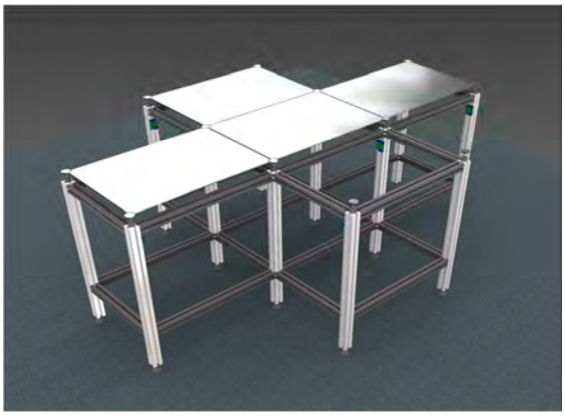

Fig. 1 The stand for complex surfaces control task's solving

The stand's equipment scheme is shown at *Fig. 2*.

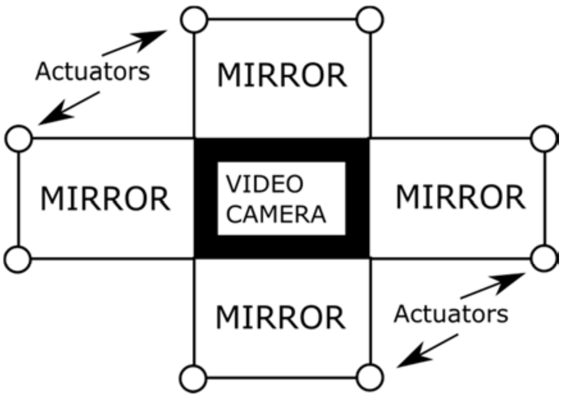

Fig. 2 The stand's scheme

The stand consists of:

- 4 moving mirrors (63.5 x 43.5 sm), 4 fixed mirrors (20 x 15 sm);
- 12 step motors of 25BYZ-B03 model ("Electroprivod" company) with step motors drivers of OMD15S model (Onitex company);
- USB web-camera of "Scout" series (Basler company);
- 4 laser rays source.

The mirror surface control requires precise displacement of every mirror, that is why it is necessary to control a position of each mirror in at least four points. We choose corner point in order to supply a minimal allowed precision. So, for mirror surfaces control they use step motors, situated in 4 corners of each mirror. The minimal linear displacement of each motor is 0.04 mm.

There were two ways how we could formalize the position of a mirror: using 4 corner motors shafts' positions or using Cartesian coordinates of laser ray, reflected from this mirror. The second way was chosen cause it not only unambiguously defines disposition of a mirror, but it also corresponds to an observed radiation reception's level stabilization task. So, we decided to use 4 fixed laser ray sources for adaptive surfaces disposition control task, because reflected laser ray's position unambiguously connected with mirror's position.

Four laser rays, sequentially reflecting from fixed and moving mirrors' surfaces is being gathered together within one A4 paper sheet (*Fig. 3*). The final position of laser ray point at sheet of paper can be matched with a mirror slope angle.

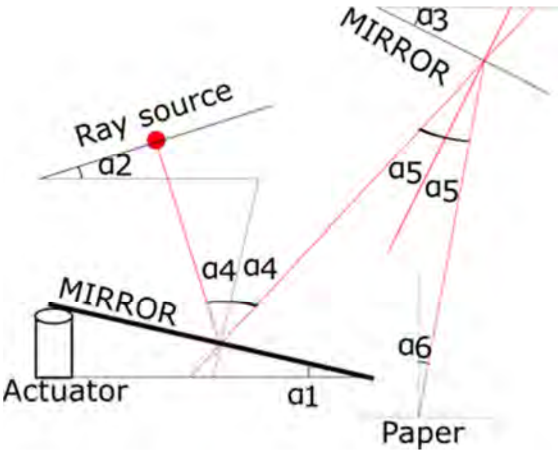

Fig. 3 Laser ray's position

Fig. 3 shows the α_1 as moving mirror slope's angle, the α_3 as fixed ceiling mirror slope's angle, the α_2 as laser ray source slope's angle, the α_4, α_5 and α_6 angles as laser rays' incident angles. It can be shown, that α_6 can be found from (1):

$$\alpha_6 = 2 * \alpha_3 - 2 * \alpha_1 - \alpha_2 \qquad (1)$$

The web-camera is used as a feedback sensor, which gets reflected laser ray points positions' image from the A4 paper sheet and transmits it to the computing station, where this image transforms to a view, shown by *Fig. 4.*

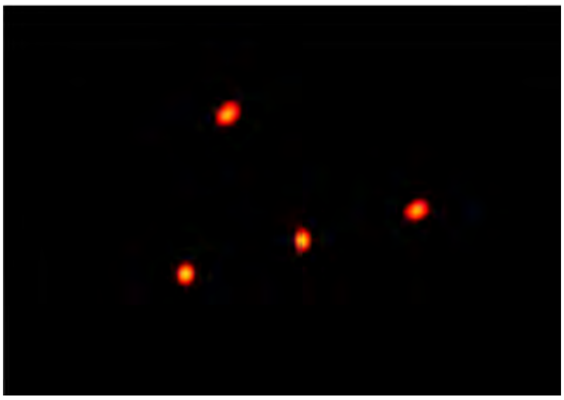

Fig. 4 The image at computing station

The orange points at *Fig. 4* have Cartesian coordinates with the origin at figure's top-left corner. The stand control task includes computing distances between each point and central point of black rectangle (point-center distance), coordinates of which are (x_c, y_c). The point-center distance can be computed by (2):

$$d = \sqrt{(x - x_c)^2 + (y - y_c)^2}, \qquad (2)$$

where *x, y* are the coordinates of point, with point-center distance is being computed. The *x, y* points depend on angle1, so $x(\alpha_1) = \mathrm{f}(\alpha_1)$ and $y(\alpha_1) = \mathrm{f}(\alpha_1)$, so we can get (3):

$$d(\alpha_1) = \sqrt{(x(\alpha_1) - x_c)^2 + (y(\alpha_1) - y_c)^2} \quad (3)$$

So, the $d(\alpha_1)$ function requires minimization:

$$d(\alpha_1) => min \qquad (4)$$

Consider the architecture of the stand's parts interaction, that can implement minimization of (4).

4 ARCHITECTURE OF THE CONTROL SYSTEM

Consider the interaction of the main functional units of the adaptive surface of the telescope. The architecture of the system components is shown in *Fig. 5.*

The computing station is used for collecting and data processing as well as for controlling actuators in such configuration. The configuration has the following disadvantages:

- the centralized scheme assumes that all computations are performed exclusively by the computing station, which reduces the performance and increases the role of the computing station;
- computing station is not able to control actuators while it's is processing while patter recognition algorithm is running

The system converted in accordance with the principles of CSP architecture is shown in *Fig.6.*

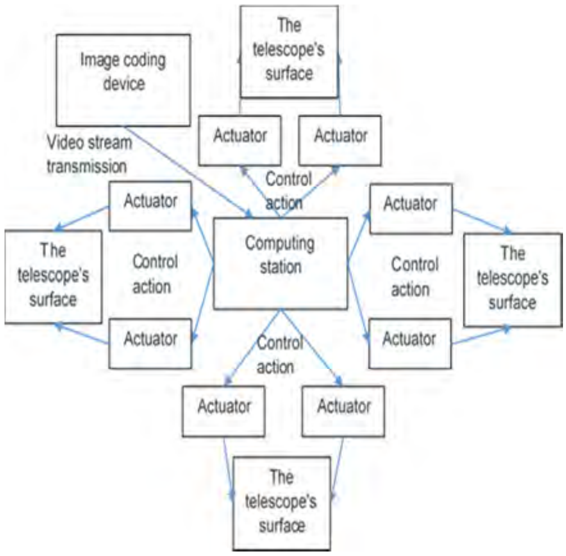

Fig. 5 Structure

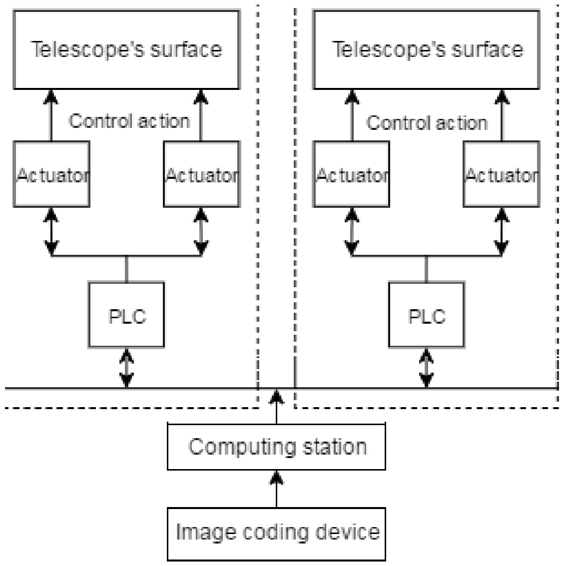

Fig. 6 The control system's functional blocks interaction scheme

The data from the image coding device contains the information about laser ray position's coordinates and contains implicit information about the surface. This data is transmitted through network protocol to the computing unit for preprocessing. A set of points is a result of data processing. The problem of matching points of the laser ray and a movable reflecting surface is also solved in the computing device. This algorithm will be given below.

Computing unit uses PROFINET to send data to appropriate PLC. The control algorithm is also implemented in the PLC groups. PLC is responsible for data collection and storing; note, that PLC shares the data with actuators as well as calculating device for analysis, logging and error notification if any.

The motor is connected to the step controller responsible for collecting information such as moving speed, direction of movement. Control sequence is sent to the motor by PLC in order to change a position of the radio telescope's mirror surface. PLC controls a set of motors, responsible for movement of a part of control object, which allows to control the position of radio telescope's surface while solving optimization issues in real-time mode. So each functional block of the system solves the positioning task independently, but is coupled to the other agents in the same time. Close interaction between lower and upper levels minimizes action required for system maintenance, as well as logging events and involving an operator in the process if it is necessary.

Next, consider the algorithms developed for the system.

5 THE MOTOR AND POINT MATCHING ALGORITHM

The first task, that intellect system should resolve in order to minimize the point-center distance is the task of motor and points matching. It means, that we should define which motor influences the specific point's displacement. Initially computing station "doesn't know" what actuator it should run to change position of each laser point, cause all four points' appearance is the same. it means, that before main program starts the system should learn which of the mirrors reflected a laser ray founded a specific point.

A sequential motors shafts positions' changing can be the best solution of this problem. it means, that we should save (x, y) coordinates of all 4 laser points, then change one specific motor shaft's position and compare all the previous and present points' coordinates in order to find the only one point which coordinates chanced.

However, there is a significant problem based on one specific property of points coordinates' recognition program: it gets points coordinates list arranged by their x-coordinates in ascending order, so a place of one specific point in this list will change if its x-coordinate changes and becomes more or less than another point's x-coordinate. So, the new task of each points' list position observation and correction appears. We need to understand if the points' order changed and if it is necessary to restore an order we had before a motor movement, because we should not let the point change its position in points' list after its motor moved even if its *x*-coordinate became more or became less than another point's *x*-coordinate.

How can we understand if one points' position in list was changed? We can find which 3 of 4 coordinates pairs didn't change. Then we can compare their places in the coordinates' list. We should not correct the points' order only if coordinates of 3 fixed points (that didn't move) are at the same list's places they were before fourth point's movement. So the only stable thing is coordinates of 3 fixed points and it helps to understand if the order change and if we should restore previous one. Consider on example. It was the list of 4 points (10, 24), (15, 40), (126, 18), (305, 98) before one motor's movement and it become (15, 40), (21, 45), (126, 18), (305, 98) after motor shaft's position changed. After comparison and unchanged points' search, the program should restore their previous order: (21, 45), (15, 40), (126, 18), (305, 98). So, the *Fig. 7* shows the matching algorithm.

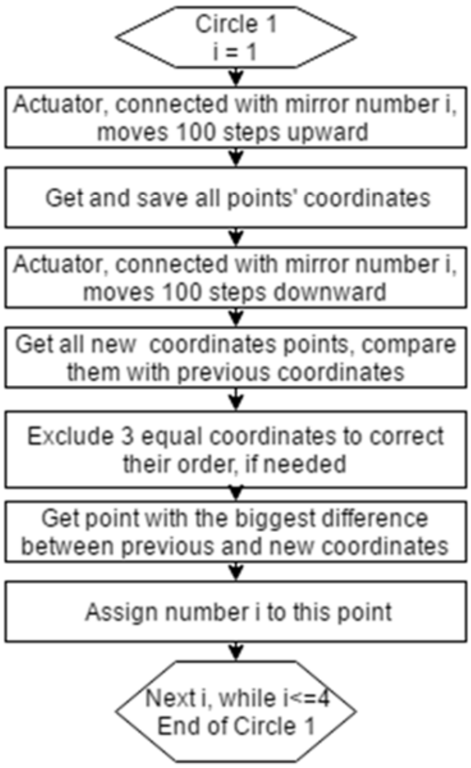

Fig. 7 The matching algorithm

Our next task is to develop main optimization algorithm, that permits to minimize point-center distance of each 4 points.

6 THE DEVELOPING OF OPTIMIZATION ALGORITHM

After each motor was matched with each laser ray's point on the mirror surface, it's necessary to develop the algorithm of function (3) minimization.

The simplest optimization method we can use is the direct search method. It can be used for the searching of the optimal motor shaft's position, which supplies the minimal point-center distance for one specific point. The main disadvantage of this method is long work time, especially if the changing interval of variable, which optimal value we are computing, is large enough.

For this method's application we need to define properties of function (3) graph: it's form and behavior. We need to understand how point-center distance changes when moving the motor matched to this point. In order to estimate this graph's form, we moved one motor from its shaft's lowest position to its shaft's highest position. Every time motor went 25 steps upwards we got point's new coordinates and computed its point-center distance. The *Fig. 8* shows one of the graphs we got during this experiment.

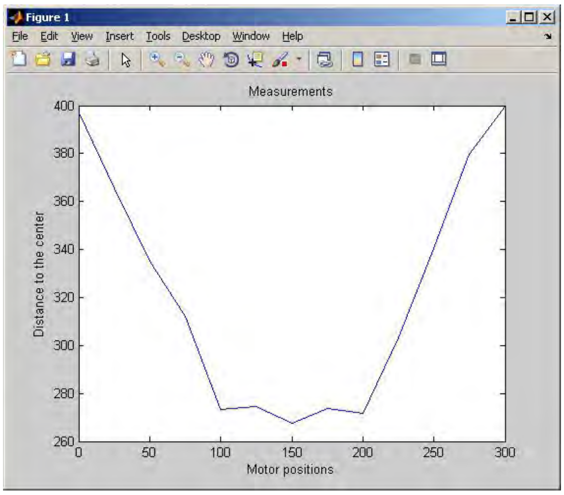

Fig. 8 The point-center distance as a function of motor shaft's position

As *Fig. 8* shows, the point-center distance graph has extreme points (more, than one), which we need to find using the direct search algorithm. Then after saving and comparing of all the values of point-center distances we can return the motor back to position with the minimal functional (3).

In this case we can solve the optimization task for motor shaft's position changing by 25 steps. New developed algorithm will be implemented by our CPS:

- The computing station recognizes the image from web-camera at the time between motor shaft's position changing and every time matches all the points with all the motors.
- After every PLC shown at *Fig. 5* gets points' coordinates matched with motors, PLC computes the point-center distance for motors controlled by it and saves it to variables as a functional we need to minimize.
- When optimal motor position is found, each PLC moves all motor controlled by him to the optimal position he got during direct search method.

Later we plan to use the constrained optimization methods for mirror surfaces positioning, but the problem is that it is difficult to choose the method before full mathematic model of laser ray's displacement depending on mirror position is developed.

7 CONCLUSION AND FURTHER TASKS

During the research a behavior models for multi-agent system coordination and architecture of cyber-physical control systems were examined. Control system of reflecting surfaces of radio telescope architecture were proposed according to principles of cyber-physical system building; the structural and functional importance of system's elements were found out; implemented solutions was estimated.

Practical part of task also consisted of evaluating optimal solution within given limitations, which are defining the range of permissible values.

Developed structural-logical models allowed to detect during analysis phase of the current system several vulnerable system nodes, for fixing which standard processing were applied. It's important to note that optimization positioning algorithms for actuators according to mutual effect on the reflecting surface is a possible direction for further investigation.

Further work in that direction is required to refine the mathematical model & optimization method selection. The most important task is to test different optimization methods using the stand in order to choose an appropriate one to be included into CPS.

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