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MECHATRONIC APPROACH TO THE DEVELOPMENT OF AN INTELLIGENT FIXTURING DEVICE TEST-BED

In order to improve the process of designing mechatronic devices, an approach, based on a mechatronic model, is proposed. The structure of such model is presented, consisting of partial models of single elements in a system. Methods of creating these models and integrating them into one mechatronic model are discussed. In order to illustrate the approach, a case study is shown, consisting of a mechatronic alignment and fixing device for high-precision machine tools. A test bed of such device is under construction, which will allow experimental verifying partial models of components, as well as the entire system's mechatronic model. An extended set of monitoring sensors will provide accurate system behaviour data useful for such process.

1. INTRODUCTION

The development of high performance manufacturing systems reaches a very high level thanks to the advancement in machining units – CNC machine tools, machining centres and last but not least, multi-function machine tools. The latter are very advanced mechanically thanks to high stiffness and geometric precision, light structure, shortening of drives – main rotational for motorspindles and, in the axes of controlled feeds, for direct linear drives. They additionally achieve high technological efficiency thanks to fine control and precision monitoring and finally thanks to highly developed software, both system and technological. Thanks to this feature it is possible to achieve very high rotational and translational speeds, as well as high precision of movements – including the reproduction of assigned outlines and positioning. A contemporary machine tool creates an extraordinarily fine mechatronic system. In this aspect, machining devices, integrated with machine tools, used for precise alignment of workpieces and their fixing in such a way, so during these operations no shape-dimensional errors are introduced to the workpiece, are far from perfection and from fulfilling the requirements set for them.

Such device, in order to equal the precise multifunctional CNC machine tools in the field of the quality and precision of realised tasks, must also be a fine mechatronic system,

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with perfectly operating mechanic, electric and electronic units, as well as its software. Many scientific centres lately undertakes more and more intensive actions in the direction of creating the scientific basis for the construction and control of such devices, oriented especially on the applications in the automotive and aviation industries, as well in the nanotechnology [1].

The structure of the advanced mechatronic device, proposed by the authors, is much more complex, because it incorporates advanced diagnostic and monitoring functions with the possibility of the optimisation of the alignment and fixing process.

A basis for the efficient operation of the proposed mechatronic device is the model. It must integrate modelling of the workpiece, which behaviour is described by a FEM model, created in Abaqus software, as well as of the actuators, accomplished in MATLAB computational software. The main problem in solving such problem is the need of applying significant simplifications to the workpiece modelling and the need of utilising highly precise experiment identifying the behaviour the workpiece itself and the contact zone of the workpiece with locators and actuators, in order to prove the correctness of corresponding simplifications. Selection of the structure of the device and its main actuation and measurement elements was imposed by such experiment requirements.

2. MECHATRONIC MODEL-BASED APPROACH

The essence of the mechatronic model-based approach is to create a fully functional virtual prototype of the entire mechatronic device, representing its behaviour in the static, quasi-static and dynamic states. It is only possible by creating partial models of the systems and then integrating them in one, mechatronic model. This allows the engineers to preview, prove concepts, and optimise their designed system before it is physically developed. Such approach can save time and money wasted on the elimination of faulty solutions from the real-life prototype. A typical structure of the mechatronic system with possible realisations of partial models integrated in one mechatronic model, is shown on Fig. 1.

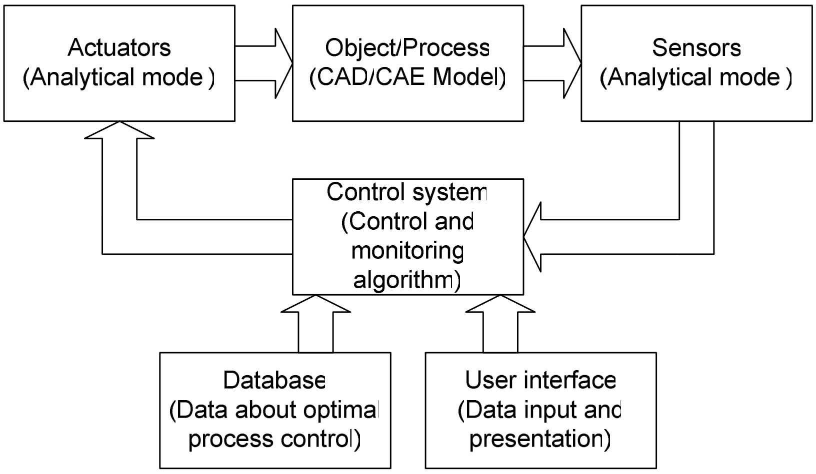

Fig. 1. Mechatronic model with its partial models

Virtual prototyping of the mechanical structure, by means of 3D models, as well as the process by means of CAE/CAM tools, is already widely used in the design process. While CAD models of a system represent only its static state, the simulations conducted in the FEM software, being part of the CAE systems, can yield answers to its quasi-static and dynamic behaviour. Such approach is presented in the paper [2].

Analytical approaches to modelling different types of actuators with regard to their dynamic properties are also realised. The paper [3] presents the approach to the analytical modelling of the piezoelectric actuator. Paper [4], in addition to the latter, also shows the analytical modelling of sensors.

A control system in the mechatronic device can be realised on devices such as the PLC's, CNC units or industrial PC's with corresponding control software. Modelling the control system can be achieved in one of the software suites for technical computing – with MathWorks MATLAB being the most popular and widely used for this purpose. Such model must contain the properly selected control algorithm, as well as the interface for operator interaction and displaying results. It must also utilise the database of optimised process parameters, chosen based on research and simulations of the object/process partial model simulations.

The main and the most difficult part of such approach is to combine all these models in one simulation system. While the analytical models of sensors and actuators, as well as the control system model can be all implemented in the technical computing environment, such as earlier mentioned MATLAB, the model of an object/process requires a different environment for conducting simulations, such as CAD/FEM software. There are three ways of solving such conflict.

One is running the simultaneous simulations in both environments with the realisation of data exchange after each simulation step. Such approach of conducting simulations of a mechatronic model was realised in the paper [5]. The authors were able put such solution in effect, because the FEM environment used for thermal calculations was developed in their research team, therefore they had a low-level access to the operation of the FEM solver. In case of the complex, multi-purpose FEM analysis tools, such as Abaqus, such each-simulation-step data exchange is not possible.

The second solution for integrating the partial models of a mechatronic model in one simulation is the integration of CAE calculations into the technical computing software, e.g. MATLAB. A Structural Dynamics Toolbox makes it possible to conduct FEM calculations in MATLAB, while FEMLink enables importing FEM models to MATLAB from the dedicated FEM software, such as Abaqus [6]. However, they are capable of handling only a limited-complexity FEM models, which is the most important disadvantage of this method. In order to import a complex FEM model developed in environments dedicated to this method must be simplified with the use of certain methods, and many significant phenomena taking place in the object/process may not be considered.

Third approach to this problem is developing the System-Level Model. In this approach, the controlled object/process is defined as a relationship between outputs and inputs, which consist of the important values of an object/process, such as forces, deformations, displacements, speeds, etc. The basis of a system-level model is a lumped parameter mathematical model that describes the physics of the system. Ordinary differential equations (ODEs) and differential algebraic equations (DAEs) express the input-to-output relationship of the mechatronic systems [7]. Such model is obtained in the process of identification, based on the experiment or a simulation, of a FEM model for example. When such model is obtained, it can be easily integrated with the remaining partial models in the technical computing environment, such as MATLAB. The main disadvantage of such method is that this model is a “black box”, which means that particular phenomena taking place inside are not considered, only the reaction of certain quantities on the stimuli introduced in form of other.

In the following chapter, a case study will be discussed, in which the attempt was made on designing the test bed, making it possible to present the mechatronic approach to the design process and to prove main concepts of it.

3. CASE STUDY FOR THE MECHATRONIC APPROACH

The goal of creating the test-bed of a mechatronic alignment and fixing system is to prove main assumptions concerning the mechatronic model-based approach to the design process, as well as to provide the possibility of testing partial models of single elements of the system. The ultimate goal is to be able to simulate the entire system in one integrated mechatronic model, supported by experimental data.

3.1 COMPOSITION OF A DEVICE

During the process of designing the control strategies, the following elements of a fixing device must be taken into consideration:

- Simplified workpiece which is the subject of the alignment and fixing processes,
- low force linear actuators used for alignment,
- high force linear actuators used for fixing,
- alignment and fixing locators equipped with force sensors,
- laser distance sensors.

Fig. 2 shows the components of a device with the indication of quantities used in the control process.

In order to conduct experimental alignment and fixing process, a simplified part has been prepared. Its selection and the studies of its behaviour have been presented in paper [2].

Linear drives consist of a stepper motor with a ball screw combined with a support constraining the rotation of a screw and allowing only for its translational movement. For low-force alignment actuators, the force exerted by them is coaxial to the translation of a screw. An actuator tip with specially chosen geometry has been used. In case of high-force fixing actuators, the force is exerted by means of rotational clamps, with direction perpendicular to the screw axis.

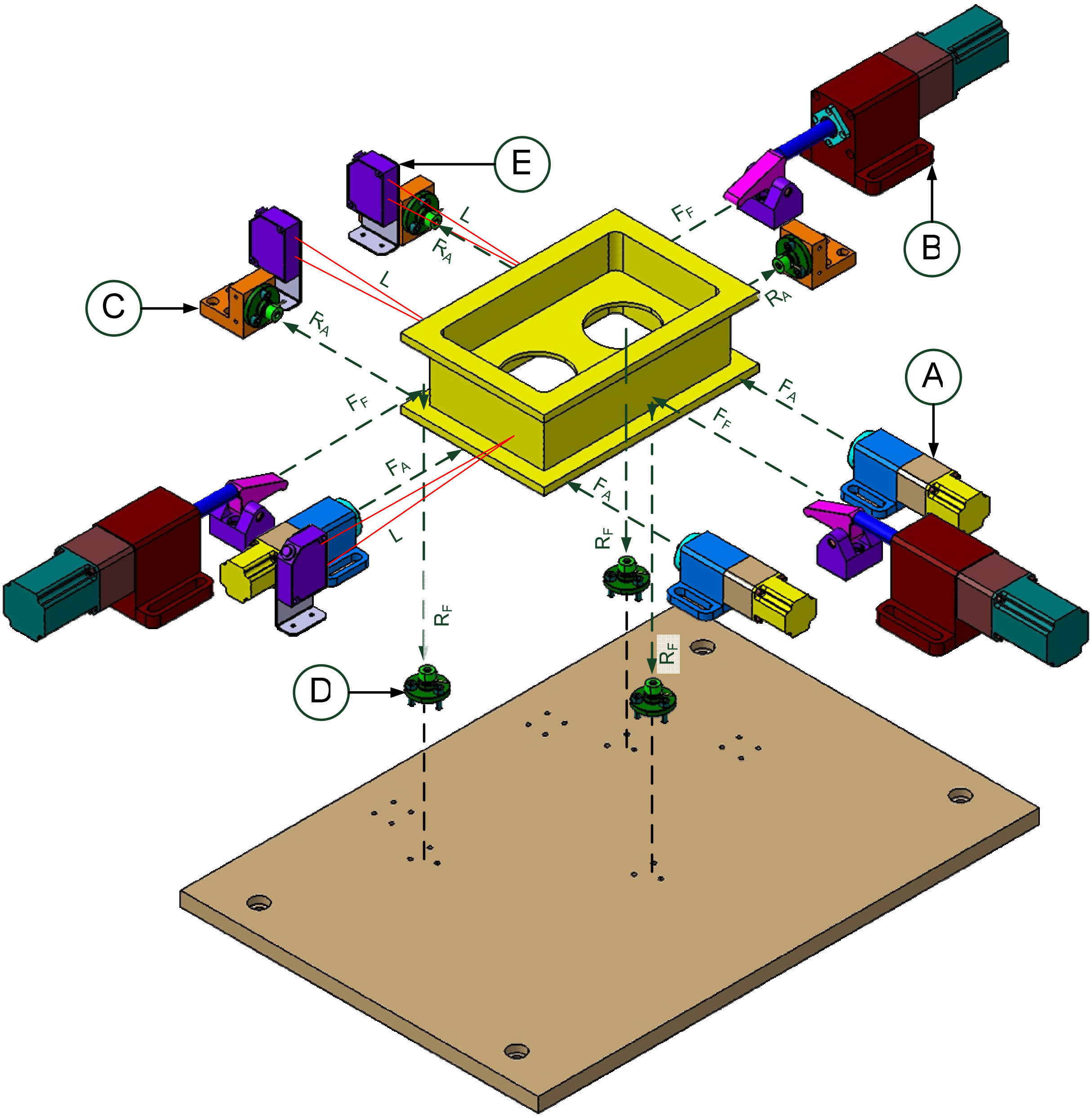

Fig. 2 Overview of a device with indications of important values;
A – alignment actuators, B – fixing actuators, C – alignment locators with force sensors, D – fixing locators with force sensors, E – laser sensors of large displacements, F_A – forces exerted by alignment actuators, F_F – forces exerted by fixing locators, R_A – reaction forces on alignment locators, R_F – reaction forces on fixing locators, L – measured distances of a workpiece from actuator tips in the rest position.

Locators are placed at the opposite side of all actuators – constraining the translation of a part parallel to the table and providing support for fixing. All locators are equipped with quartz force sensors providing information on the current reaction forces.

In order to determine the preliminary location of a part in a working area, large displacement laser sensors are used. Providing information on the distance between walls of the part and measurement surfaces, they allow for the calculation of an alignment actuator movement length before it reaches the proximity of a part wall.

3.2. MECHATRONIC MODEL-BASED APPROACH TO THE DEVICE

The mechatronic model of the alignment/fixing device, composed of partial models of mechanical and electronic elements, is shown on Fig. 3.

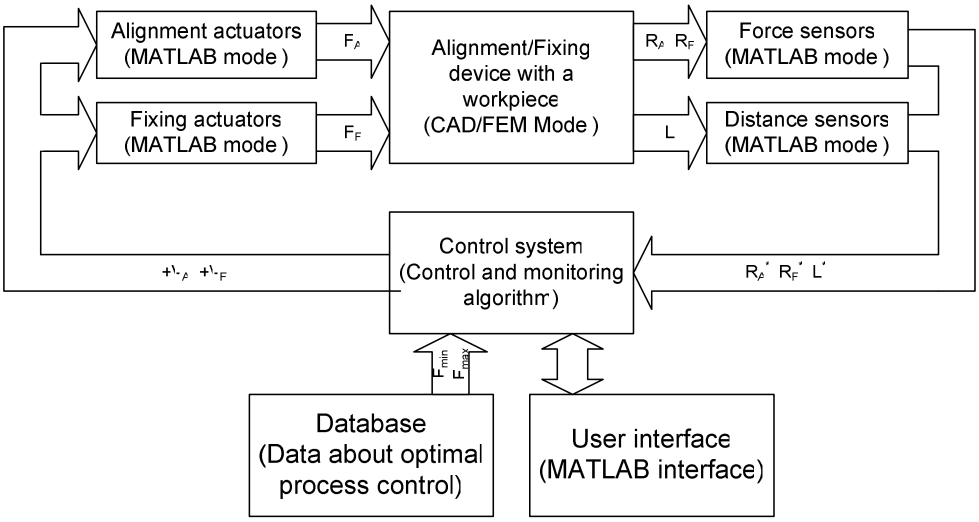

Fig. 3. Block diagram of a mechatronic system;
F_A, F_F – forces exerted by alignment and fixing actuators; +\-$_A$, +\-$_F$ – control signals of actuators; R_A, R_F – reactions on alignment and fixing locators; L – distances between the workpiece and actuators in the resting position; (*) – signals from sensors concerning given quantities.

The **model of an actuator** must reflect its mechanical, as well as electrodynamic properties. From the mechanical point of view, the actuator consists of a moving ball screw with a motor-driven nut. Therefore, the theoretical displacement of a screw is equal to the screw pitch divided by a rotational angle of a nut. This value must be corrected by elastic deformation, calculated from the equivalent actuator stiffness and a current value of force exerted on the part. Dynamic properties of the actuator, such as damping coefficient and eigenfrequencies are not taken into considerations, because of the quasi-static nature of operation.

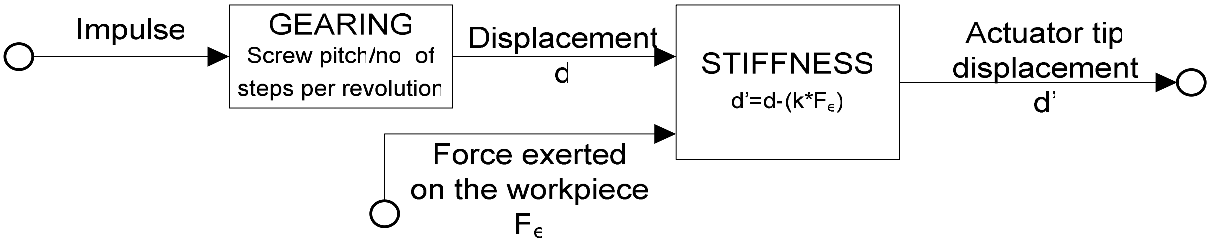

Fig. 4. Block diagram of the actuator model

The role of a **sensor model** in the system is also limited due to the quasi-static nature of measurements – the influence of their dynamic properties is also negligible. The characteristics which should be considered are resolution, precision, linearity errors, etc.

The role of a **plant** is fulfilled by a part with all static support elements. They are characterised by their kinematics when actuated, their rigidity (linear and non-linear), contact area phenomena and friction between the part and locators/actuators. To represent the nature of the plant, the alignment process must be divided into two phases:

- Moving the workpiece to achieve contacts with all touch-points (locators and actuators)
- Applying and regulating alignment forces

The first phase of alignment is to be considered as rigid body kinematics and the model needed to simulate it can be built using analytical equations or simple FEM models.

The second phase requires the consideration of the entire system's stiffness; therefore it is not possible to use rigid body mechanics. The most suitable method of modelling the plant behaviour during this phase is FEM.

The controller in this mechatronic system is the control software with implemented control algorithm.

3.3. PRESENTATION OF THE ALGORITHM

During preliminary considerations, an intuitive algorithm has been created. The control process, according to the discrete nature of drives, can be divided into elementary actions – each connected with a single step performed by a stepper motor of an active actuator. Therefore the algorithm is in form of a discrete flow-chart. Naturally, fast movements, such as approach and retraction of actuators, are not performed step-by-step, but in a single fast movement controlled directly by a motion controller, while precise movements requiring constant measurements of reaction forces are realised in such a way.

After the start of the algorithm, measurements of distances between actuators and part are realised, in order to prepare trajectories for fast movements of actuators to reach the proximity of part. These movements are then started – with a precise measurement of distances no feedback is needed. After stopping approximately 0,5 mm before the surface of a part, slow movements of actuators can begin. In this phase, every consecutive step must be preceded by the measurement of reaction forces in order to identify the moment of achieving the contact between locators and a part. When the contact has been confirmed on one of the locators, further movement is realised only by the actuator opposite to the locator with no contact. After the contact has been achieved on both locators, third actuator starts its action. First, the fast movement is realised, analogous to the movement of first two actuators. Then slow movement is commenced until the contact with a third locator is confirmed by a third force sensor. At the end of first alignment phase, all contacts are once again checked and any additional corrections are made until alignment reaction forces are in the desired range.

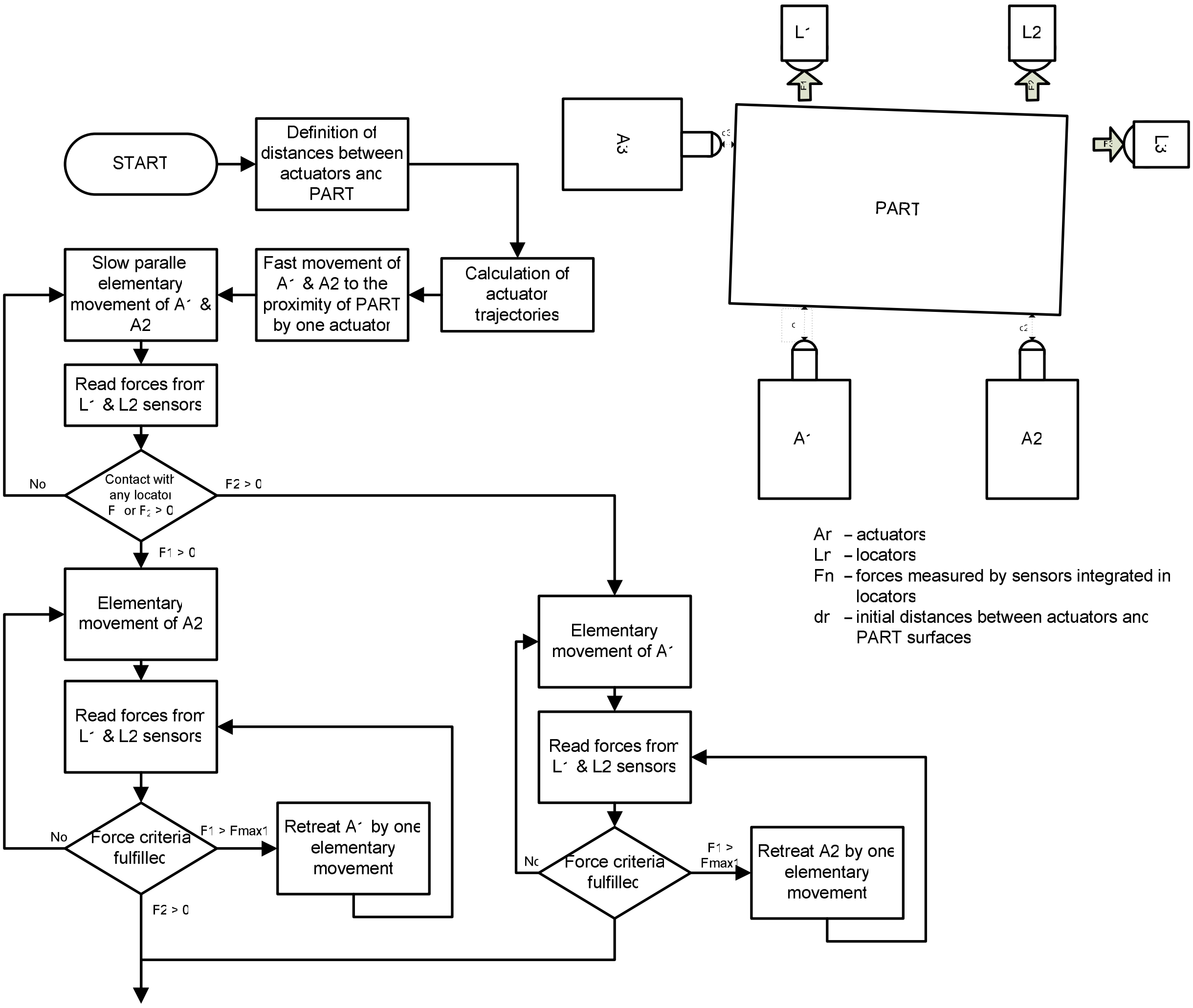

Fig. 5. Algorithm for controlling the first alignment phase

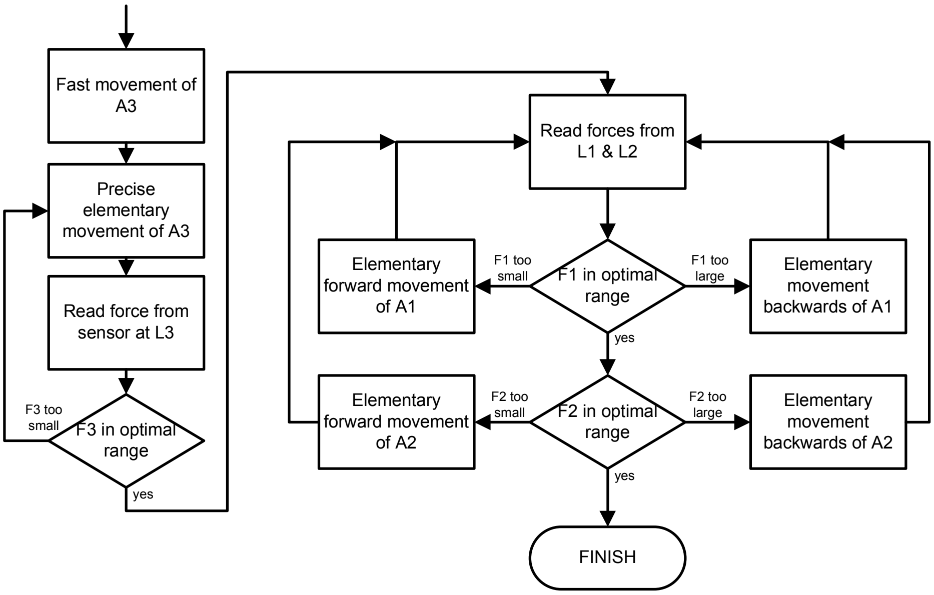

Fig. 6. Algorithm for controlling the second alignment and fixing phase

Since there are no sensors to measure the distance of rotating clamps from the surface of a part, a certain rotation can be realised in a fast way, but only to reach a safe distance to the part. The rest of rotation and applying fixing forces must be realised step-by-step, with constant monitoring of fixing reaction forces.

Due to the iterative character of the regulation of fixing forces there are possible problems with achieving alignment and fixing values within desirable range, when actuators endlessly keep adjusting the force. Additionally, such intuitive analysis of possible cases can lead to omitting procedures for handling some specific situations.

Testing and optimisation phase of a prototype algorithm must consist of two stages: model-based verification and experimental verification.

3.4. MODEL-BASED VERIFICATION OF THE ALGORITHM

A model-based verification requires the creation of a model of the system which behaves similarly to the real system. According to paragraph 2.3 there are two distinct phases of alignment, which need separate partial models. This is caused by a divergence in analysed phenomena and in the needed complexity of a model. In order to perform the simulation of the entire process in one system, a system capable of integrating different simulation tools is needed. MATLAB/Simulink computation software has the capabilities of performing such analyses and interfacing many other simulation software, such as rigid body dynamics simulation (MSC ADAMS) or finite element method solvers (ANSYS). Integrating the model in MATLAB would also be beneficial since it is a good system to implement the control algorithm in.

Another approach, which does not require integrating FEM simulation and computation software, is a “black box” model method that is based on a state-space MIMO (multi-input, multi-output) model. The model can be obtained by means of identification from learning data, acquired from FEM simulation.

3.5. EXPERIMENTAL VERIFICATION OF THE ALGORITHM

For every computer model, in order to investigate the convergence of computation results with the experimental data, an experiment should be performed. For the described system, a physical test-bed is under construction, which will make possible to prove many assumptions made for the models of its single components. Fig. 7 shows the entire set of sensors, which will be used during experimental testing. Force and large displacement sensors (1,3) are used in the control process, while the rest will only be used to gather additional, precise information about the behaviour of the system.

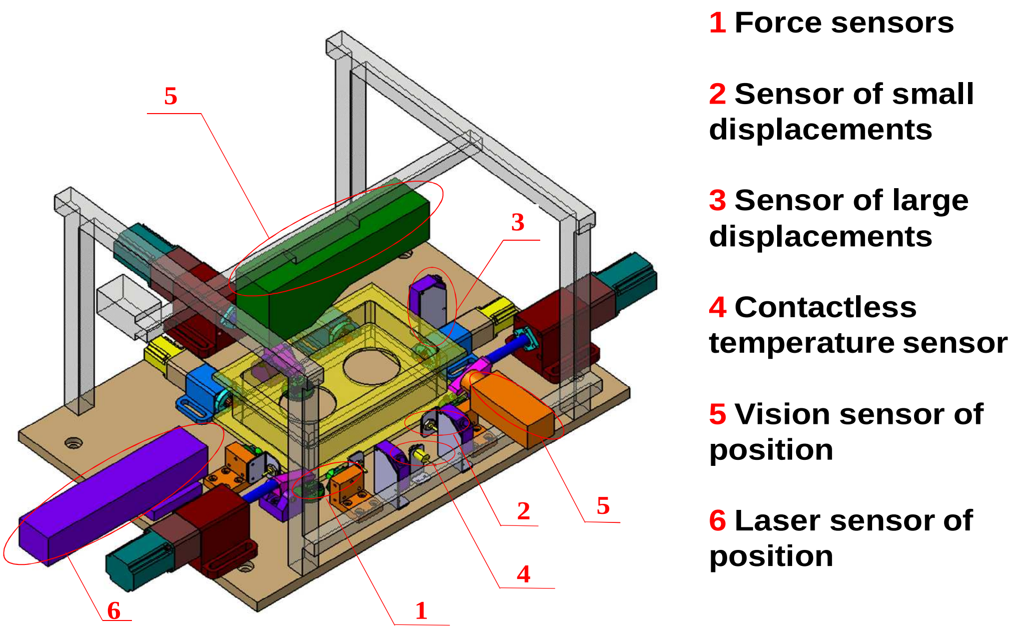

Fig. 7. Full set of sensors for the process monitoring purposes

4. CONCLUSIONS

The presented approach of mechatronic modelling clearly shows large potential for improving the design process of advanced systems consisting of mechanical and electronic components. Development of partial models of single components already starts to yield results, which will find application in mechatronic modelling. Further research activities will be focused on developing the effective way of conducting mechatronic model-based simulations, as well as expanding the model by additional components, such as the behaviour of contact areas, thermal deformations of the entire system, etc.

Thanks to the physical realisation of a prototype, which is in advanced stage, it will be possible to conduct experiments in order to prove the correctness of the assumptions for partial models. Through multiple measurements and model simulations the highest possible conformity of the mechatronic model with the real-life prototype will be pursued. Additionally, it will be possible to investigate different control strategies for the alignment/fixing process, in order to select the most beneficial one in achieving high precision and short cycle time of processes.

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