Design and Modelling of Distributed Industrial Manipulation System with Wireless Operated Moving Manipulation

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Abstract — **The paper deals with a description of principles and application concepts of a distributed industrial manipulation system containing wireless operated moving manipulation units. In the paper, there is a novel application of the wireless data communication. The solution is intended for industrial manipulation systems supporting robotic plants and centres. An example of such systems used in this paper consists of several moving manipulation units, several stationary auxiliary units and control computer.**

Keywords — Manipulation system, wireless communication, distributed systems, production lines, physical modelling, DC motors, robotics.

I. Introduction

The manipulation operations are inherent part of whatever technological procedure. Nowadays, usual modern industrial production is based on flexible manufacturing systems (FMS) and computer-integrated manufacturing (CIM) [1], [2]. It means that the systems are able to manage and react to the changes of technological procedures or technological parameters immediately when they occur. Furthermore, the manufacturing takes advantage of computers to control the entire production process. This integration allows individual system units to exchange information with each other and initiate or execute consequent actions. Due to the computer integration, the manufacturing may accelerate and be less error-prone. It gives the ability to create fully automated manufacturing processes including not only pure production operations but also manipulation operations. Typically, it relies on the closed-loop control and real-time measurements from sensors.

Specified concepts of the manufacturing are closely related to the used manipulation system. It is usually solved by production and assembly lines, which connect individual work-places of the production (see Fig. 1). The lines are fixed but composed of modular components [3]. Such configuration is advantageous for mass manufacturing and specifically for main technological flows of the production too. However, it becomes less flexible on local level, for one workplace, discontinuous or batch-mode operations or also for flexible series productions.

The requirement for the flexibility follows from the demand of highly variable production details or variable products themselves. The less flexibility of the conventional production lines consists in the fixed time cycle, fixed path or limited load capacity. Further limitations may lie in the fixed production flow of input material, finished products and waste without any consideration of different shapes, weights etc.

This paper deals with a description of principles and application concepts of the distributed industrial manipulation systems. They are introduced in the laboratory model of rail manipulation system with several independent moving units for a continuous and also discontinuous material manipulation among individual workplaces.

The flexibility is solved by the wireless data communication [4], moving and contactless sensors and adaptive algorithms of calibration/identification of key system parameters for odometry and mathematical modeling of the manipulation units. The paper follows from general features of the designed laboratory manipulation system. Thereafter, it focuses on the physical analysis and appropriate mathematical description including possible simplifications. Then, the admissible control approaches are discussed relative to the system realization and several examples from real control process are shown.

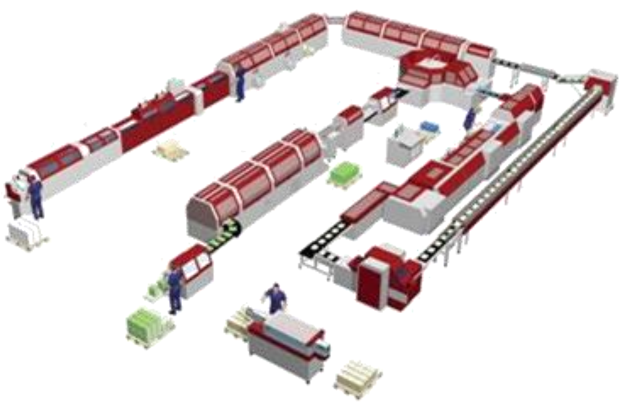

Fig. 1. Example of a production line in FMS.

Structure of Manipulation System

Let us consider a workplace with a serial robot and appropriate part of the manipulation system (Fig. 2).

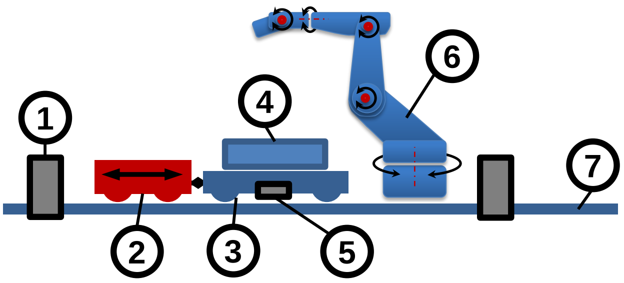

Fig. 2. Part of the manipulation system with a robotic workplace.

The workplace contains ① fixed optical gate, ② drive unit, ③ unit for load, ④ load (material, tools, products, waste etc.), ⑤ optical position sensor, ⑥ robot-manipulator (considered operations: machining, drilling, welding, varnishing, cutting, molding, packing, sorting, assembling etc.), ⑦ guide rail.

A structure of the modern manipulation system should provide flexible change of the manipulation path; collision avoiding; data exchange among individual units and some coordinator on global level (i.e. on level of the whole manipulation system); and manage variable load weight and also e.g. safety processes on the local level (i.e. relative to individual moving manipulation unit) [5].

The global-level tasks can be realized via a control computer as a main coordinator, which provides the data exchange and their processing. Such coordinator can operate in two modes: offline and online. The offline mode is determined for the preparation and evaluation of production tasks, path/trajectory optimization, making demands on the supply. The online mode provides the real-time data processing and control action generation. The local-level tasks are solved autonomously for each individual moving unit. They include the identification of physical parameters (weights and moments of inertia, electric drive constants) and calibration of position sensors.

Furthermore, the structure of the manipulation system predetermines significantly also used data transfer communication means. If the system has a fixed manipulation flow and fixed components, it is possible to consider conventional wire data carriers. For flexible structures or configurations, the wireless communication channels represent promising way of the solution. Although a wireless way offers high flexibility of the system structure or configuration, the autonomous moving units have to be equipped by some internal source of energy not only for the data transmission but mainly also for real manipulation. Generally, in case of distributed energy self-sufficient system units, the solution is searched among low-power communication technologies, which do not load the power supply of the appropriate unit and they are able to be self-restarting in failure situations.

Used hardware and software realizations taking into account principles mentioned above are demonstrated for the designed laboratory manipulation system in Section 5.

II. Mathematical Description of Componrnents

This section will focus on the mathematical description or composition of the dynamical model of one motion unit. This is due to the fact that the moving unit is a dynamic continuous system that performs the main purpose of the manipulation system. For the description of the whole system, it is sufficient to describe one unit and identify any differences of other units locally, as it was mentioned in the previous section. Differences are given e.g. by a different drive, load weight and configuration. The derivation of the dynamical model represents composition of pure equation of motion:

$$\sum_i Fi_i = \sum_j Fe_j \tag{1}$$

The equation (1) represents the dynamical equilibrium of all internal (the left side of the equation) and all external forces (the right side of the equation). Internal forces mean inertia effects and external forces mean all input effects like drive effects or surrounding effects. The detailed specification of individual terms is indicated in the following subsections.

A. External Force Effects

Let us start from description of the distribution of external force effects as the useful load and operating load in relation to the drive torque. Let surrounding effects be omitted. The basic diagram for the force distribution acting on the moving unit is shown in Fig. 3.

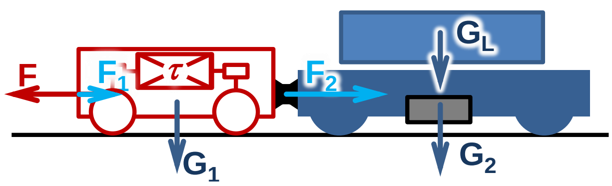

Fig. 3. Distribution of the external force effects.

The distribution of the force effects can be written as follows:

$$F \geq F_1 + F_2 = G_1\mu + (G_2 + G_L)\mu \tag{2}$$

where F is a total traction force, and F_1 and F_2 are appropriate operational and useful traction forces corresponding to the operational and real useful load, G_1, G_2, G_L are weights and μ is a coefficient of the running (motion) resistance. The force distribution (2) should meet the condition for the rolling motion of the wheels:

$$F \leq F_a = (G_1 + G_2 + G_L)\,\mu_a \tag{3}$$

where F_a is a total adhesion force, μ_a is a coefficient of adhesion friction and sum $G_1 + G_2 + G_L$ is total adhesion weight (total normal force) of the moving unit. The condition or inequality (3) is important so that the wheels of the moving units are rolled on the rail and do not slide on it [6].

Note: It is possible to consider also the magnetic [7] or air levitation motion. The former case is based on the principle of a direct linear motor; the latter is supported by traction fans.

To describe link between the driving (motor) torque and total traction force on the drive unit i.e. power transmission; let us consider the diagram in Fig. 4. This diagram represents a gear configuration of the considered laboratory manipulation system.

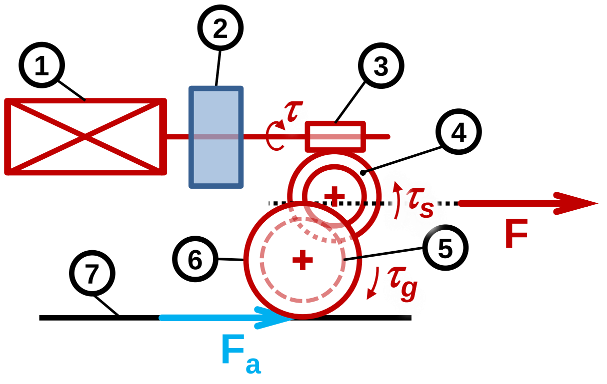

Fig. 4. Transformation of the driving torque into traction force.

The link of the power transformation includes ① unit motor (DC motor), ② flywheel, ③ worm, ④ worm with gear wheel (idler wheel), ⑤ gear wheel, ⑥ driven wheels, ⑦ guide rail. Individual force effects are the torque on the motor shaft τ, torque on worm wheel τ_s, torque on driven wheels τ_g and corresponding adhesion force F_a and traction force F. Relation among them follows from the power transmission equation:

$$P = \tau\,\omega = \tau_s\,\omega_s = \tau_g \omega_g = F\,r_w\,\omega_g = F\,v_w \tag{4}$$

where $\omega_{(\ )}$ is a symbol for appropriate individual angular velocities, r_w is radius of the driven wheels and v_w is tangential velocity on radius r_w. Then, let the following equalities of tangential velocities of the wheels in the gear mesh be taken into account:

- tangential velocity in the worm gear

$$v_s = r\,\omega = r_s\,\omega_s \rightarrow \omega_s = \frac{r}{r_s}\,\omega \tag{5}$$

- tangential velocity in the spur gear

$$v_{45} = r_4\,\omega_s = r_g\,\omega_g \rightarrow \omega_g = \frac{r_4}{r_g}\,\omega_s = \frac{r_4}{r_g}\frac{r}{r_s}\,\omega \tag{6}$$

- tangential velocity on the driven wheel

$$v_w = r_w\,\omega_g = r_w\,\frac{r_4}{r_g}\frac{r}{r_s}\,\omega \tag{7}$$

where r, r_s, r_4, r_g, r_w are the worm radiuses (motor shaft), worm wheel, wheel connected to the worm, spur gear and driven wheel respectively. Then, the dependence of the traction force on the motor torque is expressed as follows:

$$F = \frac{1}{r_w}\frac{r_g}{r_4}\frac{r_s}{r}\,\tau = \frac{1}{r_w}\frac{z_g}{z_4}\frac{z_s}{z}\,\tau = \frac{1}{r_w}\,i_{4g}\,i_s\,\tau \tag{8}$$

where z, z_s, z_4, z_g are numbers of teeth of the appropriate wheels and i_{4g}, i_s are the gear ratios of the spur gear and worm.

B. Model of the DC Motor

The DC motor represents the simplest motor configuration. It can be modelled by the second order equation as follows:

$$\ddot{\tau} + \frac{R}{L}\,\dot{\tau} + \frac{k_{m1}\,k_{m2}}{J\,L}\,\tau = \frac{k_{m1}}{L}\,\dot{u} \tag{9}$$

Its graphical representation is shown in Fig. 5.

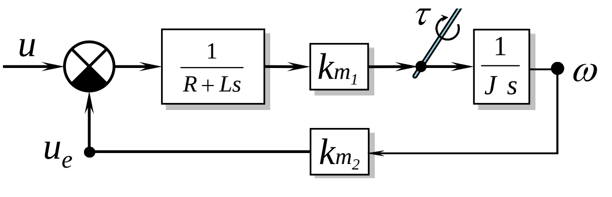

Fig. 5. Diagram of the DC motor.

The diagram is for the brush DC motor with permanent magnet in the stator; u, u_e are input and internal induced voltages; J is moment of inertia of the motor shaft and other parameters R, L, km_1, km_2 are electrical constants – resistance, inductance, current and voltage constants [8].

C. Internal Force Effects

As was already mentioned, internal force effects represent inertia effects. In the case of the moving unit, they are caused predominantly by the weights of individual parts of the moving units. Thus, they are described by the following expression:

$$\sum_i Fi_i = (m_1 + m_2 + m_L)\,\ddot{x} \tag{10}$$

D. Dynamical Model of Moving Unt

Full description of the dynamics of the moving unit (pure equation of the motion) consists only of the dynamical equilibrium of the force effects in horizontal direction (single longitudinal axis), i.e. internal and external effects including modelling of the unit drive. For the purposes of the control the dynamics of the drive can be modelled by a linear dependency. The suitable model of the moving unit can be expressed as follows (repetition of (1) from the beginning of this section):

$$\sum_i Fi_i = \sum_j Fe_j \tag{11}$$

The complete model can be written after the appropriate substitutions as:

$$(m_1 + m_2 + m_L)\,\ddot{x} = F \tag{12}$$

$$F = \frac{1}{r_w}\,i_{4g}\,i_s\,\tau = \sum_j Fe_j \tag{13}$$

$$\ddot{\tau} + \frac{R}{L}\,\dot{\tau} + \frac{k_{m1}\,k_{m2}}{J\,L}\,\tau = \frac{k_{m1}}{L}\,\dot{u} \tag{14}$$

The equations (12) - (14) represent complete dynamical model of one moving manipulation unit. This detailed mathematical model is suitable as a simulation model. For a control purpose, it can be simplified. The possible model simplification will be shown in the following section.

III. Control Approaches

The control of a distributed manipulation system represents hierarchical or multilevel task. On the highest global level, the control algorithms have to provide save manipulation (manipulation without unit collision) and optimal manipulation trajectories among individual stand positions. This level is a logistic task [1].

The local level relates to the individual moving manipulation units. The control task on this level can be defined as follows:

"Let the reference values for the motion trajectory or its forthcoming trajectory segment of individual manipulation unit be given, then the task of control is to generate such control actions to follow the given reference and to meet accurately required stand positions."

For completeness, an additional level, the lowest one, provides data communication tasks and data preprocessing. This level is important, when the wireless communication among individual manipulation units and communication with the system coordinator is used.

In this paper, a fully-bidirectional wireless ZigBee communication is considered [9]. It provides data transmission from the central coordination computer to the individual manipulation units and vice versa.

From the control theory point of view, the following three main control approaches can be taken into account:

- switching two-level or multi-level logical control
- simple PID control (control error evaluation)
- model-based control (e.g. Linear-Quadratic control)

The first approach uses a limited control action set, from which the appropriate control action is selected according a few predefined switching rules. It provides discontinuous fitful manipulation. This approach is suitable for small systems with low weight of loads.

The other two approaches use continuously data from the measurement and generate control actions in their full range of admissible drive inputs. It can offer smooth motion without sharp and sudden oscillations.

Simple PID control does not use model, it evaluates only control error of the measured system output from the reference values. The model-based control approach is based on a more complex optimization algorithm including mathematical model of the individual manipulation units [10].

For laboratory purposes, it is possible to consider a simplification of the mathematical model given by (12)–(14):

$$(m_1 + m_2 + m_L)\,\ddot{x} \;=\; k\,u \qquad (15)$$

It follows from the assumption of the steady state behavior of the particular unit. Then, the model of motor dynamics can be given for small powers by a linear function:

$$\tau \;=\; k_u\,u \qquad (16)$$

where k_u is a voltage coefficient. All constant coefficients can be condensed in one coefficient k as follows:

$$k = k_g\,k_u \qquad (17)$$

where k_g is obtained from the gear ratios:

$$k_g = \frac{1}{r_w}\,i_{4g}\,i_s \qquad (18)$$

The model (15) is used in case of a non-adaptive model-based controller. Other possibility is to consider some identification for determination of the model parameters [10].

IV. Realization and Examples

This section is focused on a brief description of the used laboratory model of the distributed manipulation system. The system (see Fig. 7) consists of several distributed moving units and stationary units. The moving units provide discontinued manipulative operations and the stationary units serve as a monitoring and utility interface. Both moving and stationary units are independent of other units (autonomous of others) in all respects, i.e. self-controlling and energy self-sufficient units. The units are driven by DC motors and contain electro-optical position sensors and are equipped by ZigBee communication transceivers (transmitter & receiver in one) [11]. The transceivers are connected to the ZigBee communication network.

The network is realized as a star network with one main node working as the network router and coordinator. It comprises a gateway for the control computer, which provides both the global and local level control. The lowest level is provided directly by the main node (Fig. 6).

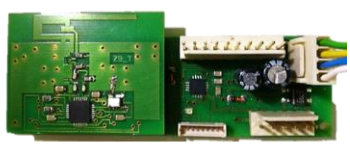

Fig. 6. ZigBee network router & coordinator all in one node.

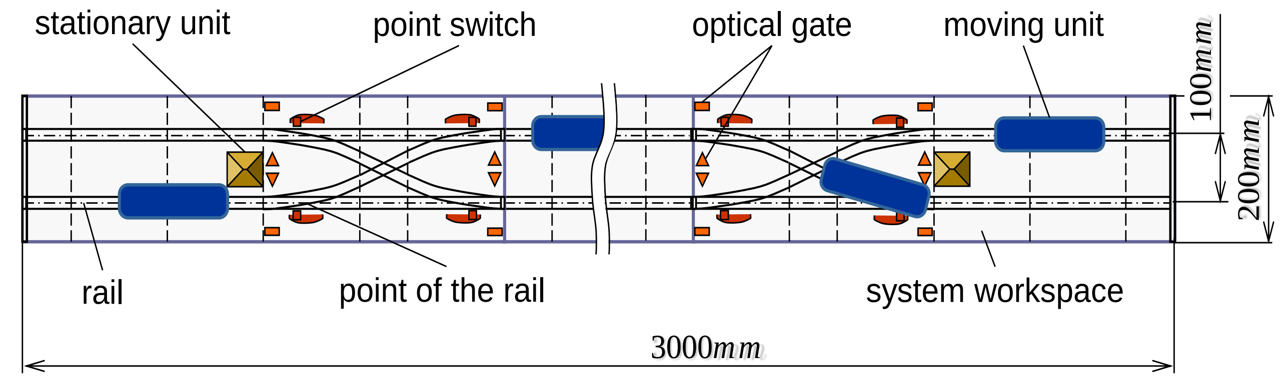

Fig. 7. Diagram of the laboratory manipulation system.

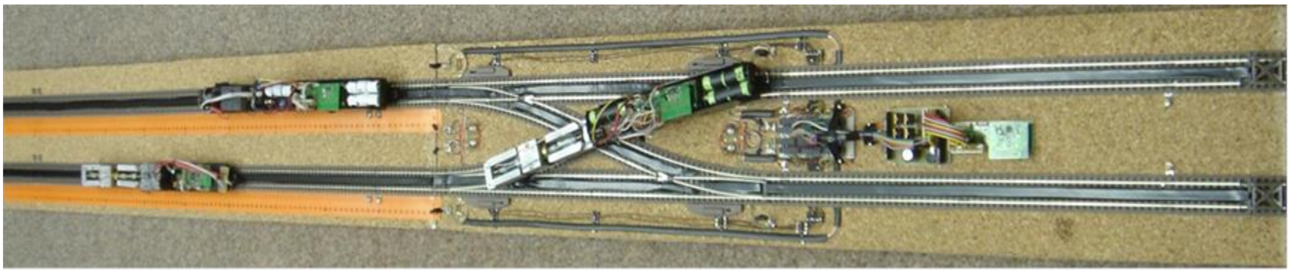

Fig. 8. Real laboratory model of the manipulation system.

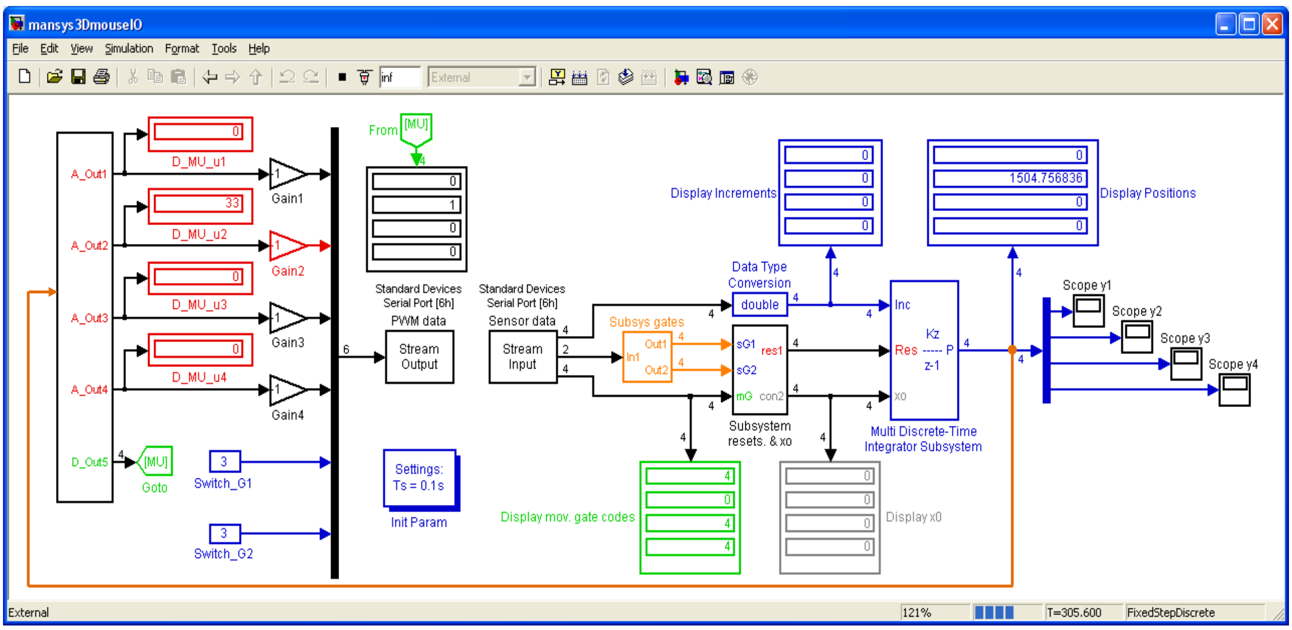

Fig. 9. Screen shot of the real-time control circuit in the MATLAB-Simulink environment.

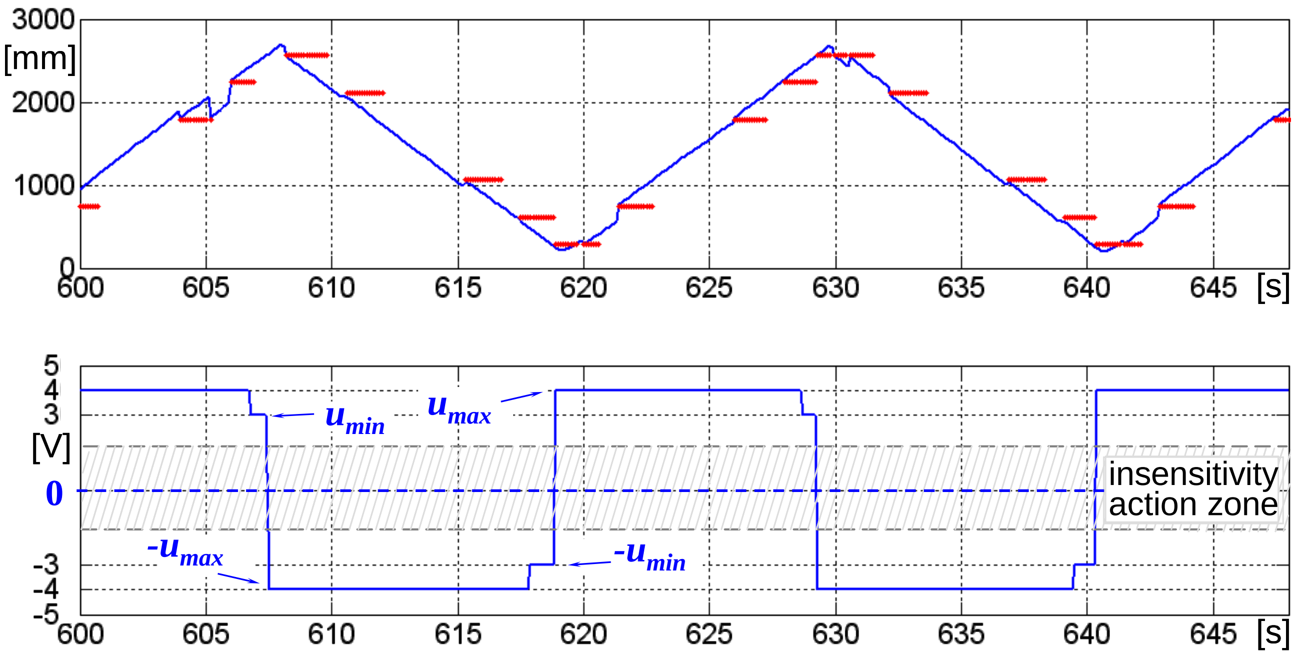

Fig. 10. Time behaviour of one moving unit: position (on the top) and control actions (at the bottom).

Fig. 11. Example of the moving manipulation unit.

Fig. 8 shows half of the laboratory model of the manipulation system. In Fig. 8, there are three moving units, four point switches and four fixed optical gates.

Fig. 9 shows the used real-time control circuit implemented in the MATLAB-Simulink environment intended for the tests of the simultaneous cyclic motion of the moving manipulation units.

The circuit is prepared for up to four moving units with individual optical position and optical gate sensors and two stationary units with eight point switches and eight fixed optical gates.

Stationary units provide operations of the point switches and fixed optical gates. The gates serve for determination of the absolute positions of all units, which contains only incremental position sensors.

The system itself is connected within the Simulink model via Standard Devices Serial Port - Stream Output (PWM data) and Input (Sensordata) Simulink blocks. The Input - Output blocks provide communication with a serial interface of the control computer.

Fig. 10 shows time behaviour of one moving unit during a cyclic motion. The position is on the top. At the bottom, there are appropriate control actions. The time behaviour was recorded for the switching multi-level feedback control. The control algorithm selected control actions discretely relative to a topical unit position (positional feedback).

In Fig. 10, the resets of the position measurements of the incremental optical position sensor are indicated by the red horizontal short lines. They correspond to appropriate signals from the fixed optical gates of the manipulation system.

To pass the gate means that a particular moving unit interrupts the optical circuit and the corresponding fixed optical sensor of the gate sends a coded message to the computer for processing.

The data records in Fig. 10 show occasional failures in the position estimate. It can be caused by an imperfect surface for the optical sensor. The ZigBee communication had no failures in the data transmission. These failures may occur, if the transmitted signal is low or is blocked by some obstacle.

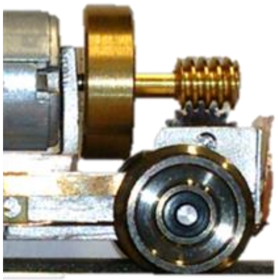

Fig. 12. Gears of the drive unit.

Finally, Fig. 11 shows an example of one moving unit and Fig. 12 shows a detail view on the transmission of the driving torque from the shaft of the DC motor by the gears on the driven wheels of the drive unit. Fig. 12 closely corresponds to the diagram in Fig. 4.

V. Conclusion

The paper deals with a mathematical physical analysis for composition of the mathematical model of the moving manipulation unit as main dynamical part of a distributed manipulation system. In the paper, the technical aspects of the control approaches were discussed.

The aim of the future investigation and development is a complete application of the multistep model based predictive control [10] on level of the individual moving manipulation units of the manipulation system as a distributed autonomous control configuration. Predictive control as a model based approach would consider model (15) and generate an appropriate level of the input voltage for the particular moving manipulation unit.

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