Interactive Control Systems for Mobile Cranes

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Abstract. The paper presents an invented interactive control system for mobile lifting devices, particularly for loader cranes. The proposed innovative system is comprised of modules, output signals from which are sequentially transformed into a commands sequence corresponding to the motion strategy, related to incremental changes of position or motions depending on the distance to the end position. In the system, the commands sequence related to the position of the operating element corresponds to the trajectory optimization strategy in accordance with the positioning time minimization criterion, total length of the path of motion minimization during handling, or maximization of the safety indicator. An innovative processing scheme, using several functional modules, for the interactive control system has been presented, covering also the use of anti-patterns of normalized commands and standardized strategies, and analysis of crane stability. The invented system solves the problem of effectively controlling lifting devices during tasks requiring increased efficiency, safety, speed and precision.

Keywords: Interactive control · Innovative control · Smart control systems · Human-machine interaction · Mobile lifting devices · Loader cranes · Speech interface · Natural language processing

1 Innovative Smart Control Systems

Lifting devices are tremendously utilized in numerous heavy load transportation industries, and therefore, the control of mobile loader cranes is becoming an interesting and important research field. Recent research has led to making significant improvements in new developments and new patents [1] in the field of control systems. Recent advances in development of prototypes of speech-based control systems are described in [2–10].

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Innovative control systems feature speech-based interactive communication [4–11], machine vision - vision systems [12], augmented reality [13] as well as interactive controllers [14,15] providing force feedback. The systems for smart control of mobile cranes can consist of diverse components: speech and natural language processing methods [16,17], tracking cameras, augmented reality goggles, laser trackers, geometry and topography scanners, photogrammetric cameras, movement scanners, interactive manipulators, measurement tools, sensors for signal acquisition, actuators for performing or triggering actions.

Smart control of mobile cranes incorporate functions of sensing of device working conditions and environment, actuation and control of mechanical and mechatronic systems, in order to analyze and model a task or situation, and make decisions based on the acquired data in a predictive or adaptive manner, thereby performing smart control actions for the lifting device and processes. Advanced smart control systems address safety, efficiency and ergonomic challenges like automation, optimization [18], supervision [19], flexibility, adaptability, robustness, and the ability to reuse knowledge. They are for that reason increasingly used in a large number of different tasks. Key sectors in this context are construction, transportation, logistics and manufacturing [20,21].

Interactive control systems for mobile loader cranes equipped with Internet of Things (IoT) modules can monitor and connect device's components, tools and operators. The crane type and tasks specifies what data is needed and where to locate sensors. Real-time data on the task progress and conditions can change the scope of supervision. The IoT consists of sensing, communicating and analyzing data to visualize the information gathered to improve operator performance, from the operating zone to the maintenance centre. Another approach is application of IoT and embedding electronics inside the tools for sensing to get information and also controlling the process. It will also include process-execution and supervision engines to monitor operations and provide real-time quality feedback.

2 Safety Systems for Mobile Loader Cranes

The safety in working with cranes is absolutely important. The proposed approach to interactive control systems [1] has proven crucial and very useful in crane load handling systems. The safety of the control system includes analysis of crane stability for various load conditions and trajectories of load translocation [22,23]. During the operation cycle, the analysis of mobile crane load handling system stability for selected configurations and operating conditions is performed. It is an important task, because a failure to consider stability conditions in dynamics of the real crane arrangement may lead to loss of stability. As the results of the analysis, variations in stability conditions depending on angular position of the turning column with booms and telescopic booms, positions of telescopic booms, values of boom angle of elevation, load-bearing system components masses as well as on crane loading are processed by the safety system.

The safety of the control system also includes analysis of the support system reactions for the assessment of mobile crane stability [24]. The developed module is used for computing the ground reaction forces of the crane support system in the entire operating range. The verification of the mathematical model was performed using the finite element method. The results of numerical computations were used to analyze the stability of the mobile crane load handling system for selected configurations and operating conditions. The results of the simulation provide changes of the reaction forces in the support system and the envelope of the load path for given load capacities and reach of the crane.

The novelty of the proposed interactive control system [1] also consists of inclusion of several functional modules for: determination of strategies of operation moves, sequences of coordinational commands, sequences of incremental commands, optimization of movement trajectories, checking safety indicator, ensuring collision-free movements, control of positions, comparison of actual and nominal positions, evaluation of task completion based on actual and nominal positions correspondence, as well as analysis of crane stability.

3 Interactive Control Systems for Mobile Cranes

The invented modular system for interactive control of a lifting device (Fig. 1) is proposed in the patent application [1]. The system (Fig. 2) is made up of modules which output signals are sequentially transformed creating decisions on motion strategy and position evaluation, which have impact on filling or terminating the commands sequence in the performed task.

The system solves the problem of effectively controlling a lifting device during tasks requiring increased efficiency and a high level of safety, as well as in conditions of increased requirements in terms of speed and precision. The system uses the commands sequence related to the operating elements position together with the information from the position control module and creates that sequence while taking into account trajectory optimization strategy. The advantage of this system is the minimization of the time of positioning. Another property is the minimization of the total length of the path travelled during positioning. The next property is the maximization of the handling safety indicator. Yet another property is such that command sequences are transformed into constituent movements and trajectory optimization strategy, taking into account the traits of objects within the listing devices zone of operation.

The tasks of the system can be described in abbreviated form. The task given by the operator in the form of spoken, symbolic or impulse commands goes to the motion strategy module, which is responsible for choosing the strategy of motion. After choosing a strategy of motion a signal is sent to the coordination commands sequence module, and then to the incremental commands module. After the strategy has been accepted by the command validation and safety of execution module, the handling action is performed from the current position to the nominal one, which at the same time is the task itself. The task is accomplished when the nominal position is reached, that is after the position control module sends a signal to the current and nominal positions comparison module, while simultaneously the task completion evaluation based on actual and nominal positions correspondence module is also working.

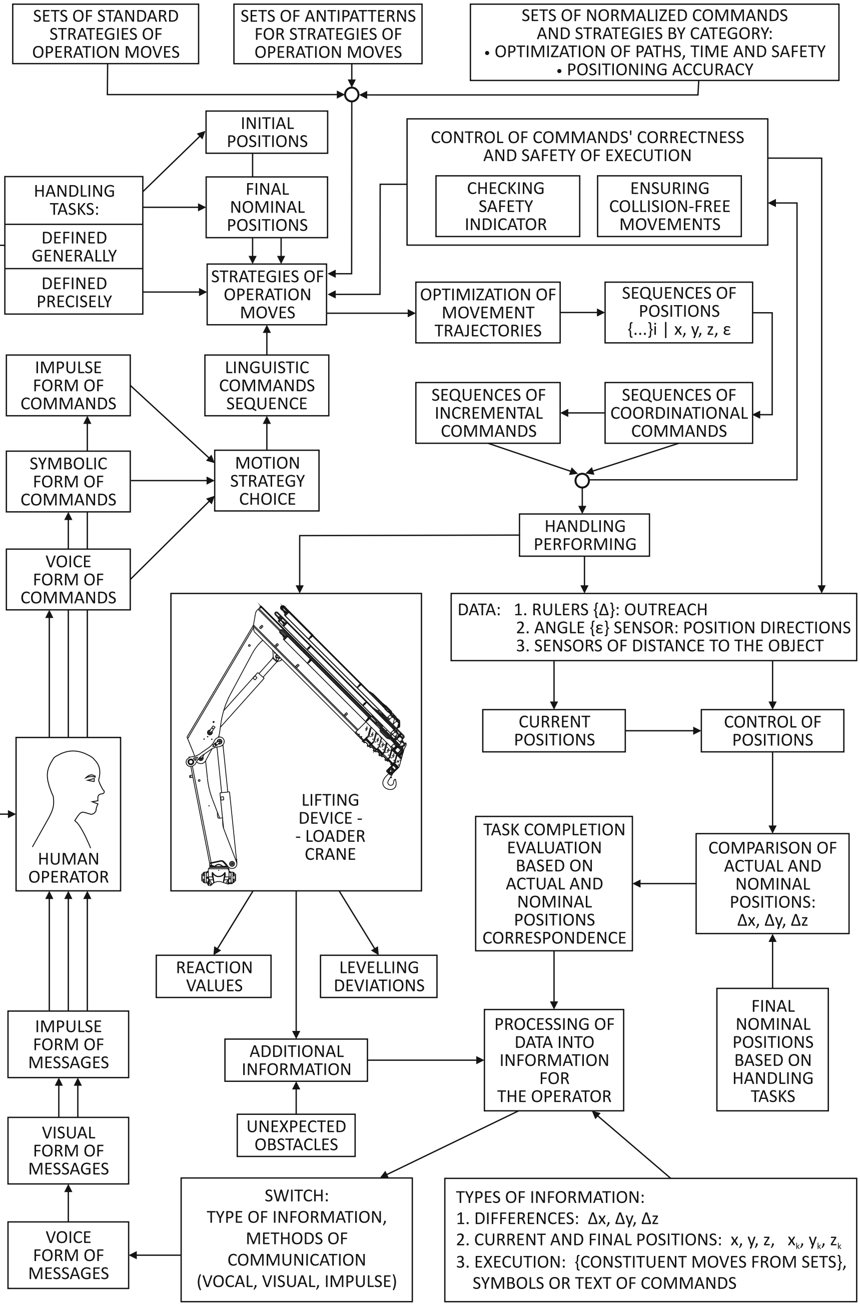

Fig. 1. Interactive control systems for mobile cranes (based on [1]).

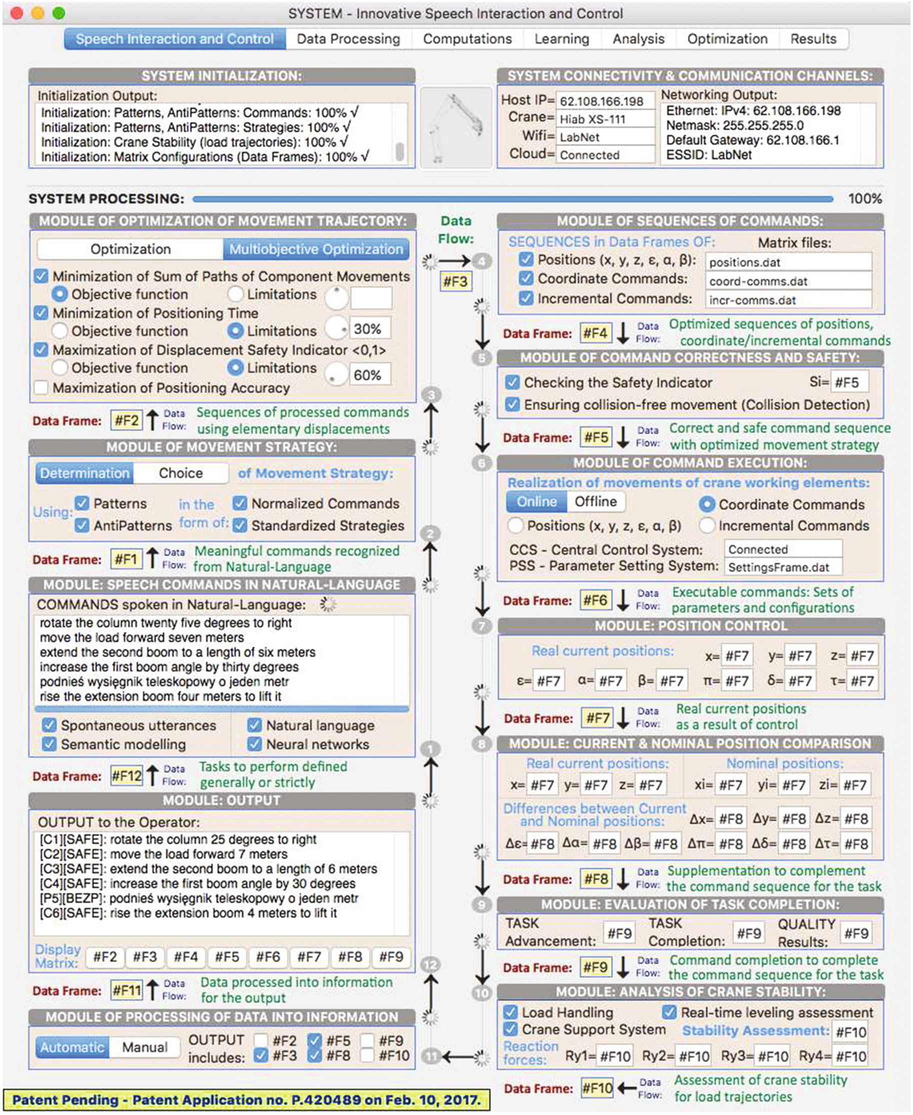

Fig. 2. The developed software for interactive control of mobile loader cranes.

The system is characterized by the fact that it is comprised of modules, output signals from which are sequentially transformed into a commands sequence corresponding to the motion strategy, related to incremental changes of position or motions depending on the distance to the end position. The system is also characterized by the fact that continuation of the commands sequence related to the crane operating elements position depends on the result of the position control performer by the module. The system is also characterized by

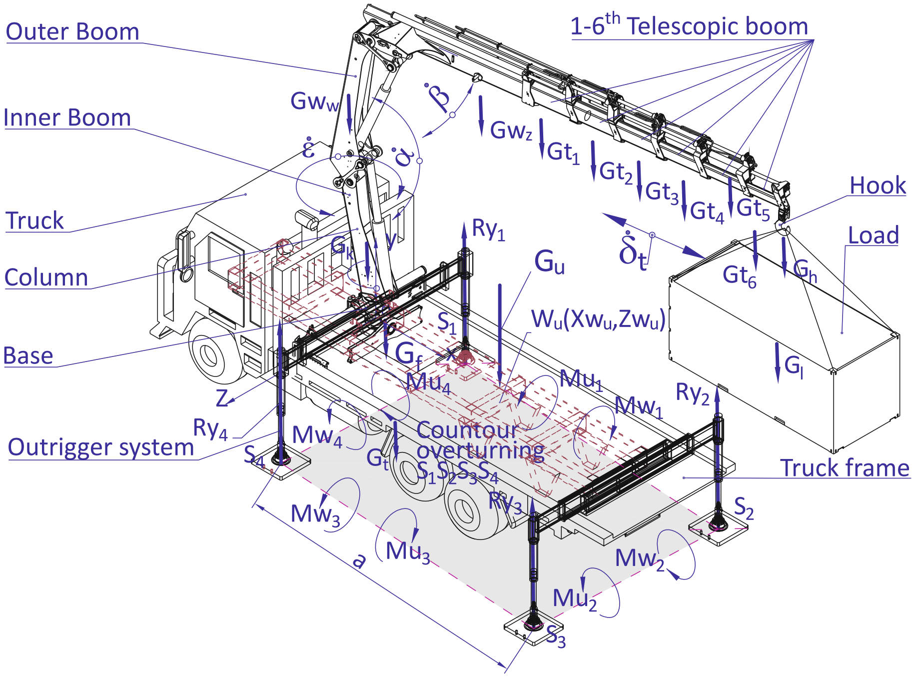

Fig. 3. Diagram of forces and torques that act on the crane outrigger system: where: Gu - total weight of the crane system; Gf - weight of the truck including the outrigger system; Gb - crane base weight; Gk - weight of the slewing column; Gw_w - weight of the inner arm, Gw_z - weight of the outer arm; Gm_1, Gm_2 - weights of hydraulic cylinders; Gt_1, Gt_2, ..., Gt_6 - weights of the arms of the six-member crane boom; Gh - hook weight, Gl - cargo weight; Ry_1, Ry_2, Ry_3, Ry_4 - vertical reactions of the base; a&b - spacing of the crane outriggers.

the fact that the commands sequence related to the position of the operating element corresponds to the trajectory optimization strategy in accordance with the positioning time minimization criterion, total length of the path of motion minimization during handling, or maximization of the safety indicator.

The safety subsystem of the crane load handling system (Fig. 3) incorporates the optimization of cargo displacement trajectory and assessment of mobile loader crane stability.

When planning the trajectory of the movement, safe and fast transport of the cargo, one needs to ensure that the planned points of the path are reached and to ensure the accuracy of the final cargo positioning. It is important to ensure at the same time the minimization of the path length of the cargo transported and of the execution time of the handling assignment. In a general case, the optimization problem consisted in seeking the vector of decision variables, for which the defined objective function reaches the minimum:

$$min\ L_l = f(x)_t \tag{1}$$

where:

- L_l - path length of the cargo transported,
- x - vector of decision variables that contains the configuration parameters of the crane handling system [22],
- t, s - handling assignment cycle time.

The length of path L_l was calculated from the following formulas (2) and (3):

$$L_l = \sum_{j=0}^{n-1} (L_{j-1} + \Delta L_j) \tag{2}$$

$$\Delta L_j = \sqrt{(x_{L_j} - x_{L_j-1})^2 + (y_{L_j} - y_{L_j-1})^2 + (z_{L_j} - z_{L_j-1})^2} \tag{3}$$

where:

- ΔL_j - increment of the path of the cargo transported in time Δt,
- $x_{L_j}, y_{L_j}, z_{L_j}$ - current coordinates of the cargo location.

An analytical description of the configuration of the crane (configuration parameters) consisted in replacing vector equations with homogeneous matrices transformations, which contain the matrices of the rotations and translations of the local systems of the coordinates of the crane system elements [22,23]. It needs to be emphasized, however, that it is very troublesome to obtain open dependencies. Hence, to determine these vectors, the crane simulation model and the numerical applications developed were used.

Inequality constraints were imposed on the decision variables. They follow from the stability conditions of the crane system (Fig. 3), which are as follows:

1. According to international standards [25] and PN [26] it is accepted that the crane is stable if at any position of the boom loaded with lifting capacity with an adequate extension, the stabilizing torque M_u is greater than the overturning torque M_w by the value of ΔM (4):

$$\Delta M = M_u - M_w > 0 \tag{4}$$

2. The value of the pressure on the base of the least loaded crane support and the value of the changes of this force in time [24];
3. The location of the symmetric mass centre of the handling system of the crane in relation to the support points [22]. The system is stable if, in the projection on the horizontal plane, the mass centre is located inside the quadrangle that is established by the support points of the mobile loader crane outrigger system;
4. Safety indicator W_b as the stability criterion of the crane system, which was defined as (5):

$$W_b = min \in \left\{ \frac{min(Ry_i)_t}{G_u \cdot k_1 \cdot (1 - k_2)} - \frac{k_2}{1 - k_2} \right\}_t \tag{5}$$

where:

- $i = 1 \div 4$ - number of the outrigger,
- j - number of the elementary fragment of the trajectory,
- $min(Ry_i)$, kN - the smallest of the vertical reactions of the base on the outrigger i,
- G_u, kN - total weight of the crane system,
- k_1 - index of the maximum load of the crane outrigger, $Ry_{max} = G_u \cdot k_1$, where: $k_1 \leq 0.25$ - for a crane with four outriggers,
- k_2 - index that determines the minimum load of the crane outrigger, $Ry_{min} = G_u \cdot k_2$,
- t, s - time of the working cycle of the handling assignment.

In order to guarantee the stability of the crane system, the value of the indicator W_b should be greater than zero when $min(Ry_i) > k_1 \cdot k_2$. The value of the indicator k_2 is determined considering safety on the level that depends from the crane working conditions. It was accepted that the value of this index takes into account the wind speed as well as the velocities, accelerations and pulls in the crane kinematic pairs. Pulls may be the result of the cargo frozen to the ground being torn off, the cargo being broken off, sudden breaking, hitting an obstacle etc.

4 Conclusions and Perspectives

In the past few years, smart control systems have attracted a great deal of attention from both academia and industry due to many challenging research problems and a wide range of applications. The paper presented an invented interactive control system for mobile cranes. The invented system solves the problem of effectively controlling lifting devices during tasks requiring increased efficiency, safety, speed and precision.

The novelty of the proposed interactive control system consists of developed functional modules for: strategies of operation moves, sequences of coordinational commands, sequences of incremental commands, optimization of movement trajectories, checking safety indicator, ensuring collision-free movements, control of positions, comparison of actual and nominal positions, evaluation of task completion based on actual and nominal positions correspondence, as well as analysis of crane stability. Innovative control systems designed for processes of precise positioning of objects and heavy cargo can be equipped with intelligent interaction systems between lifting devices and their human operators.

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