AN INTEGRATED APPROACH TO THE DEVELOPMENT OF CONSTRUCTION SITE CRANE OPERATIONS

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VTT is the abbreviation of the Technical Research Centre of Finland.

ABSTRACT

The following is a review of the current status and future plans of the research concerning tower crane operations, carried out by the Technical Research Centre of Finland (VTT).

Firstly, an empirical time-motion study of crane operations on building sites is described. The results can be used for creating a crane selection guideline in a textual or knowledge based form and in crane automation ideas evaluation.

Secondly, the current crane automation research results carried out by VTT are summarized and possible applications to a tower crane are characterized.

Thirdly, some of the future activities in crane automation research in VTT are discussed. In those studies an integrated approach to crane automation problems will be applied, where development of the site's overall order, systematic construction management methods, knowledge or simulation based crane selection methods, adaptation of building components and crane automation will be gradually combined on the way to the long term goal: a highly automated building frame erection system.

1. INTRODUCTION

The use of tower cranes on construction sites has stabilized during the past few years after having decreased due to rapid proliferation of mobile cranes. The speed at which tower cranes can be installed and dismantled has increased and tower cranes seem to be the more economically viable choice on those sites, where a hoisting device is needed for at least a couple of weeks and the required range is moderate.

However, although the tower crane is a crucial piece of construction equipment in frame erection, most of its technical principles have been developed already during the 1950's. The evolution of the tower crane has been considerably slow.

VTT has carried out a feasibility study on construction robotics, and by means of interviews it was discovered, that the contractors have set some new requirements for tower cranes in the long term. The most urgent prospects are:

- to attain more flexibility in the crane's mobility on-site
- to simplify and speed up the installation and dismantling of the crane
- to enhance accessories like videosystems, tele-operation, autonomous power sources and load-specific tooling for automatic gripping and releasing
- to develop computer controlled systems for autonomous work cycles and for the stabilization of the suspending load
- to develop methods to position the loads and to install them by actuators
- to clarify the factors relevant to the selection of a crane and to develop a project manager's aid for the selection.

These items have been seen to impact on the working process in the following ways, which are already traditional reasons for justifying construction robotics:

- increasing the productivity by means of faster working cycles, by improving tower crane service capability, by longer daily utilization time and by decreasing the number of workers needed
- enhancing the working environment's safety by pre-determined trajectories, where obstacles and human working areas are taken into account, and by radically reducing accidents when installing prefabricated components
- improving the quality, which is a consequence of smaller tolerances that are requisite for an automated frame erection
- amending the controllability of the entirely frame phase by efficient crane selection methods and by more predictable utilization of the crane.

VTT has started a comprehensive study on construction robotics for the years 1988-1990, where the automation questions of the tower crane will be examined as one of the pilot projects. The basis for this research is, on the one hand, a time-motion study of crane operations on building sites, and on the other hand, current general purpose crane automation projects in VTT. In this paper, we discuss the earlier work and future aims in this area.

2. THE USE OF TOWER CRANES ON-SITE: PROBLEMS AND PROSPECTS

<u>Goals and contents of the crane use study</u>

The Laboratory of Building Production Technology has carried out an empirical research, where the tower crane operations were monitored during 4000 lifts. For every lift, the contents and the weight of the load, the point of time, the duration, the transfer distance and the lifting height were registered. On the basis of these data, the average lift duration for each material was estimated and the impact of the transfer distance, the weight of the load and the lifting moment on the lift durations was analyzed. Furthermore, a model for determining the crane capacity needed in the frame erection phase was developed. The results can also be used in crane automation ideas evaluation.

<u>The use of cranes on building sites during frame erection</u>

The results of the study indicate that the percentage of the effective crane time from the total working time is almost constant (70 - 75 %) in the frame erection phase, regardless of the type of building.

The lifts directly related to the production of the structural frame (concrete, components, formwork, reinforcement) make up 55-60 % of the effective crane time. The lifts of timber, plates and metal wares demand 5 - 15 % of the effective crane time. The share of the lifts related to various machines and equipment is surprisingly high, on a site for precast concrete component buildings as much as 20 %.

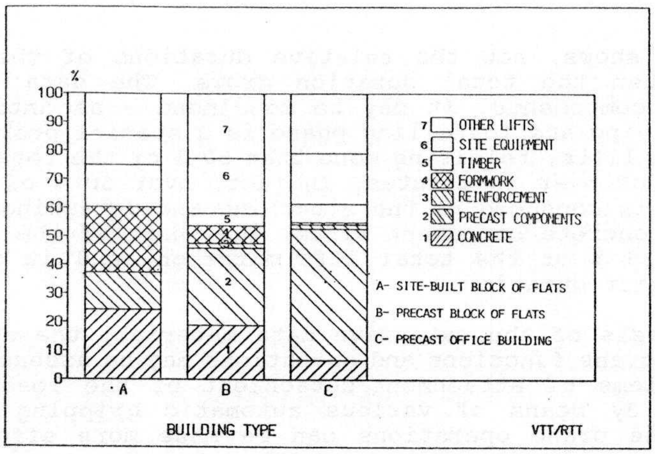

Figure 1. The use of a tower crane during the erection of a concrete frame (by effective time).

Average lift durations

The lift durations typically obey the distribution presented in Figure 2. More than 50 % of the lifts in the sample were shorter than 4 minutes, and 5 - 15 % of the lifts had a duration of more than 15 minutes. As for the lifts of precast concrete components, the share of long (over 15 minutes) lifts was as high as 15 %. In comparison, the corresponding figure for concrete lifts was 5-7 %.

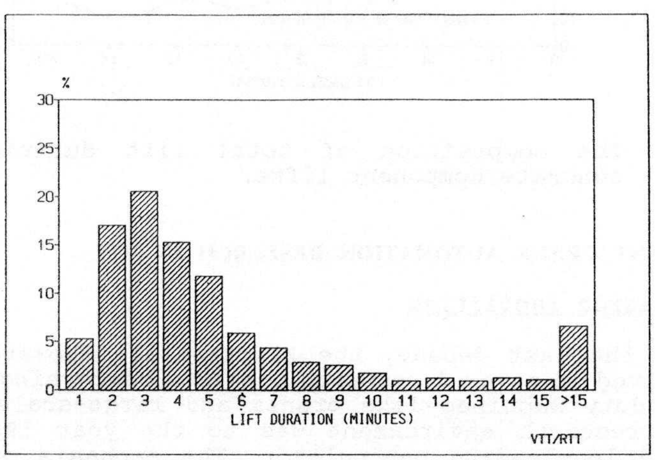

Figure 2. The distribution of lift durations (all lifts).

In order to be able to isolate the causes for the increase in lift durations, the individual lifts were broken down into the following phases:

* the transfer of the hook to the load and the waiting/preparation of the lift
* the gripping of the hook to the load
* the transfer of the load to the destination
* the receiving/installing of the load and the releasing of the hook.

Figure 3 shows, how the relative durations of these lift phases change when the total duration grows. The data is for precast concrete components. It may be concluded - as anticipated - that the receiving and installing phase is a special problem in concrete component lifts, requiring more than 50 % of the total lift duration in lifts of over 15 minutes. In fact, over 60 % of the total lift duration is consumed by the attaching and detaching of the load in precast concrete component lifts. The share of the actual transfer is only 25 % of the total lift duration, and it diminishes with growing lift duration.

On the basis of the extensive data material, the development need of tower crane functions and operations may be assessed. Especially, the problems of attachment/detachment of the load should be addressed. By means of various automatic gripping and attachment tools, the crane operations can be made more effective, and the labour requirements can be reduced.

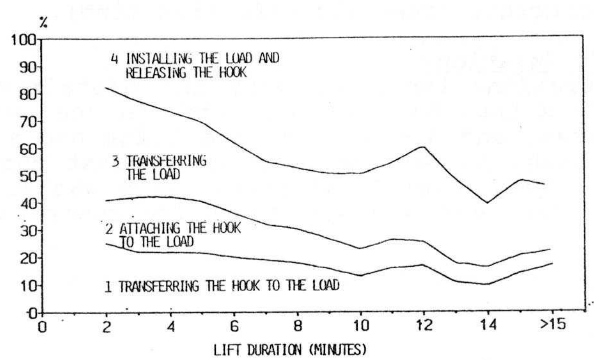

Figure 3. The composition of total lift duration in precast concrete component lifts.

3. CURRENT CRANE AUTOMATION RESEARCH IN VTT

3.1 Research facilities

During the last decade, the Electronics Laboratory of VTT has been involved in several research projects concerning the automation of heavy duty machines like cranes and large-scale manipulators. The main research environment was to the year 1985 a computer-controlled log-loading manipulator. The emphasis of the work was on two main aspects. The first one was to develop computer-based instrumentation and control methods for digital servo control, and the second one to develop interactive, model-based control and programming methods suitable for manipulator control in unstructured and dynamic environment [3, 4, 9].

At present, the crane automation research is part of the VTT's mechatronics research, which emphasizes an integrated, multidisciplinary approach to the system design of robotic machinery. The current crane automation research environment, see Figure 4, has been constructed from the end of the year 1986 around a rotary crane typically used for container handling in harbors.

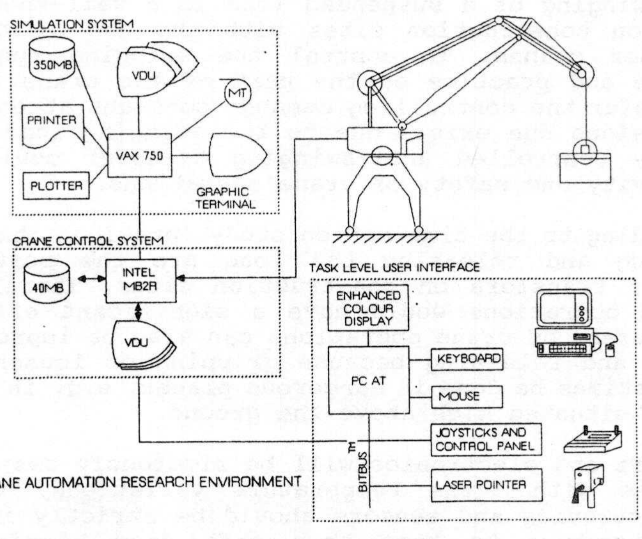

Figure 4. Crane automation research environment.

The control system is divided into two hierarchical levels. The lower level takes care of the servo control including path generation and the control of elementary movements, while the upper level acts as an intelligent man-machine interface by which the crane operator can describe the environment and the desired activity by task-oriented commands. In addition, the crane control system is joined to a simulation system which is used for control design and operational simulations.

3.2 Current research topics and their contribution to construction

Current crane automation research topics in VTT can be categorized into four main areas:

1. Crane control methods for unstructured, dynamic and severe environments.
2. Anti-swinging control of a suspended load.
3. Gripper positioning for automated grasping of objects to be transferred.
4. Reliable electronics and sensors for harsh environments.

Although the work in these areas has been initiated within the context of materials handling in a harbor or a factory, it has turned out that it is highly relevant also for construction.

The first research area has an immediate connection to construction because the construction robots and cranes operate in an environment that is less structured, more dynamic, more complex and more severe than the environment of manufacturing robots. Many operations on construction sites include unpredictable events and therefore preprogrammable machines can seldom be applied. On the other hand, developing of totally autonomous machines will be costly besides the technical difficulties. Thus, a natural solution is to use the human operator's versatility in perception, planning and control.

The swinging of a suspended load is a well-known problem which appears on construction sites with the use of tower cranes and some other cranes. To control the swinging requires a lot of expertise and practice on the part of the crane operator. During the transfer the controlling demands constant attention; the danger of collisions due exists due to the swinging load. Thus, an automatically controlled anti-swinging transfer could increase both productivity and safety of crane operations.

According to the time-motion study (previous chapter), grasping, installing and releasing the load are the most time-consuming phases of transfers on construction sites. Therefore, automation of these operations would have a significant effect on productivity. Safety of crane operations can also be improved by automated grasping and releasing because gripping or loosening of the hook must sometimes be done in dangerous places, e.g. in narrow, slippery surfaces situated high above the ground.

Sensors and electronics will be rigorously tested on construction sites with large temperature variations, vibrations, dust etc. Electronics and sensors should be strictly integrated to the crane structure to keep them safe from harmful environmental effects.

3.3 The technologies concerned

Interactive task-level control

The concept VTT has developed for the control of heavy duty machines is called an interactive task-level control, and it is based on the use of a 3D measuring device, a laser pointer, and a graphics user interface [6]. In the interactive task-level control the operator concentrates on environment modelling, task descriptions and execution monitoring instead of the continuous steering of the crane.

The modelling is based on the use of simple geometric primitives and their combinations. The operator can define a solid geometric object (e.g. a cube or a cylinder) by pointing only a few coordinates with the laser pointer according to the instructions of the computer, see Fig. 5. If some parameters of the object are known beforehand, the number of pointings can be reduced.

After the environment has been modelled to the computer, the operator describes tasks by task-oriented commands like transfer, load etc. The actual coordinates of a start point or an end point of a transfer can also be given with the laser pointer by the operator. The operator can use the graphic user interface both in verification of the model and the tasks by simulation and in monitoring task execution.

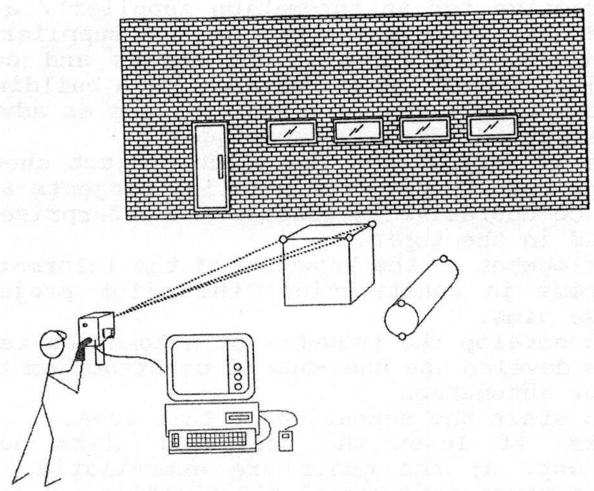

Figure 5. Defining objects by the laser pointer connected to the interactive task-level control.

Anti-swinging control
The method used in anti-swinging control of a suspended load is based on the optimal control theory. At the beginning of the transfer a minimum time criterion is applied to transfer the load quickly to the neighborhood of the destination. The accurate positioning to the equilibrium state is then performed by applying a quadratic minimization criterion. The sensor for measuring the swinging is based on ultrasonic technology.

Gripper positioning
The technologies which are under research for gripper positioning include ultrasonic based measuring systems, fiber-optic sensor systems, 2D camera systems and laser range-finding based sensors, including a 3D vision system [5].

Reliable electronics
The developing of reliable electronics for harsh environments has concentrated on integrating and packaging the electronics mechatronically into the sensors, actuators and control systems.

4. FUTURE RESEARCH STRATEGY: AN INTEGRATED APPROACH

VTT will carry out in 1988-1990 a research programme "Information and Automation Systems in Construction" [1], where construction robotics pilot projects play a crucial role. At the moment, a crane automation development is most probably one of them.

The following choice criteria have been used for the selection of each pilot project:

1. Need in production. This includes factors like productivity, work safety, improvement of the working environment, working in previously impossible environment, quality assurance, material waste reduction, better controllability of the building process etc.

2. Attractive for an automation supplier / a building material producer, which means that a) the supplier must be convinced by the device's sufficient market and coverage or b) the project should add extra value for a building material product by creating a system which combines an advanced material and an advanced assembly technique.
3. Synergy influences: the pilot project should be contributed to by results got from parallel projects at home and abroad, and co-operative institutes and enterprises should be interested in the topic.
4. Development of the know-how of the information and automation systems in construction; the pilot project should support these aims:
   - to develop the know-how of automation technology
   - to develop the know-how of construction technology suitable for automation
   - to start the education of this area.
5. Risks. At least the following risks must be taken into account: a) the goals are unrealistic, b) robots on-site might cause some social difficulties, c) the objective of the project is realized overseas by much more competitive resources and d) an impressive failure is accomplished, which will freeze construction robotics progress for a long time in Finland.

In the crane project, an integrated approach will be applied, where the subject is divided into five main areas:

1. Gradual development of automated crane operations, i.e. sensing and control systems, accessories and the site's measurement systems connected to the crane control.
2. Development of guidelines and procedures for crane selection (instructions, knowledge and simulation based computer aids).
3. Adaptation of construction systems (components, details and joints) suitable for an automated erection.
4. Questions concerning the interfaces between a) 3D model of the building and the crane and b) the site's project management system and the computer controlled equipment for materials handling and storaging.
5. The overall systematization and development of the site order and project management methods, which are the genesis for site automation.

It seems that an integrated approach will respond to the criteria 1-4 quite favourably. The risks are, nevertheless, considerable. The technical problems are difficult and complicated.

Crane suppliers are very interested in automation of crane operations (for instance Potain [2], other development topics, see [8]). Some contractors (like Condis by Takenaka [7]) have also demonstrated their interest. Nevertheless, due to criteria 1-4 there seems to be a need also for a wider approach.

<u>Automation of the crane operations</u>

The automation needs of the crane operations can be classified as follows:

1. automation of the trajectories of frequent work cycles
2. automated gripping and releasing
3. automated changing of tools and grippers

4. actuator-based positioning of the load
5. automated installation of the components
6. enhancement of high level control methods like task oriented control, interactive control and tele-operated control.

An analysis of the economic and technical feasibility of each of the mentioned automation themes is underway. Nevertheless, to reach these automation goals, the following subtasks must be accomplished:

1. If the crane operator will tele-operate the crane from the ground, lots of valuable, partly cognitive knowledge will disappear by losing the buttocks-based sensing system from the tower. This sets high reliability requirements for the crane's load, moment and balance sensing system.
2. The stabilizing and controlling of the swinging load, a problem which has been discussed earlier.

Development of the construction system

The design of each pre-fabricated component must be adapted for the whole system. The adaptation requires the following questions to be considered:

- Tolerances of pre-fabricated components and the constructed frame must be extremely limited.
- Chamfered, self-adjusting and self-locking joints must be developed to speed up the assembly and eliminate slips etc. during the installation of the components.
- The components should be stacked downward to utilize the gravity.
- The component's grasping points must be compatible for automated gripping and releasing. The assurance of a safe grasping must be reliable enough, for example video monitoring combined with a sensing device.

Testing environments

To evaluate those automation operation ideas created during the pilot phase, the following testing environment stages have been planned:

1. Computer simulation of the ideas for technical and economical evaluation.
2. Construction of a miniature model c. 1:10 for laboratory environment.
3. Use of the first full-size prototype in a storage of a concrete component factory, which can be modelled quite smoothly due to the more structured environment.
4. The next full-size testing environment might be standardized buildings. A type of small house and a steelframed power plant are suggested.
5. The last testing environment will be a generic construction site.

Crane selection methods

Alongside the automation efforts, some guidelines for the crane selection will be developed:

1. The Finnish construction industry has developed a comprehensive collection of productivity files (called RATU-files), which include among other things method information and work, materials and equipment rates. A new crane selection

instruction will be publishéd in the near future based on the time-motion study.

2. Some of the RATU-domains have already been represented in an expert system form. A knowledge based crane selection system is under consideration.
3. Technical and economical questions of each crane automation problem, like cycle times and constructability analyses, might be clarified by a computer graphic representation. Different kinds of simulation/animation methods have been planned for this purpose.

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