Automatic Control of road Construction Machinery – Feasibility and Requirements

Rauno Heikkilä, Mika Jaakkola

Oulu University, Research of Construction Technology
P.O.Box 4400 (Kasarmintie 4), FIN-90014 Oulu, Finland
rauno.heikkila@oulu.fi, mika.jaakkola@oulu.fi

ABSTRACT: A wide range of construction machines are used in the course of road building. Automation offers a number of benefits and improvements to the control of the work processes. A total of 16 different work procedures involving 13 construction machines were evaluated using the measurement criteria developed for this purpose. Total points scored by the procedures varied from 8 for 15 (maximum being 22, minimum -11, the average 11.4, and standard deviation 2.0). Only one of the work procedures evaluated in the course of study was found to be unsuitable for automation. The criteria were developed to highlight the essential features and details required for further automation in road construction.

KEYWORDS: automation, road construction, heavy machinery, feasibility evaluation, measurement criteria

1. INTRODUCTION

This paper evaluates the applicability of automation to the control of road construction machines in Finland. The aim of the study was to discuss the feasibility of the automation of the most commonly used road construction work procedures and machines and related requirements. A general field study was carried out to enable the feasibility study.

A total of eleven indicators were developed to evaluate earlier experiments with the automation of road construction machines. The feasibility of automation for each work procedure was assessed using these criteria. The machine control system of a motor grader was used as a frame of reference for the evaluation of other machines. The functional idea of these instruments was to emphasise essential specifics that are regarded as fundamental for considering automation for road construction methods. The following criteria were used for the feasibility evaluation:

1. Does the work procedure include any repetitive task?
2. Is it possible to mechanise the work procedure or has it already been mechanised?
3. Is there any potential for minimising material losses?
4. Does automation improve the overall efficiency of the work procedure?
5. Are the requirements for geometric accuracy essential in the work procedure?
6. Is the design data required for machine control available?
7. How technically complicated is the implementation of automatic control?
8. Does the work procedure involve any tasks that are dangerous or hazardous to human health?
9. Does automation improve the competitiveness of the contractor?
10. Does automation improve the standard of quality of road structures?
11. Does automation in road construction promote sustainable development and improve the state of the environment?

2. MATERIALS AND METHODS

2.1 Measurement criteria

A total of eleven (11) indicators or criteria were developed in the course of the present study to allow an objective identification and evaluation of the potential for automation in road construction. Naturally, these indicators do not cover all the aspects and prerequisites for automation. However, it was established that these eleven indicators give a fairly extensive presentation of the factors illustrating the importance of automation in road construction. The main purpose of the indicators developed in the course of the evaluation of the potential for automation was to identify and highlight the individual factors affecting automation. At the same time, the results of the measurements made and their comparison are likely to offer some guidelines for further research and product development. The indicators were:

1. *Does the work procedure include any repetitive task?*

This indicator is based on the idea that the greater the number of individual, identical, repetitive "standardizable" tasks that a specific work procedure includes, the easier it is to automate it. Conversely, a lower number of such identical tasks means that automation is difficult.

2. *Is it possible to mechanise the work procedure or has it already been mechanised?*

One of the prerequisites for automating any work procedure is its potential for mechanisation. What this indicator seeks to illustrate is the degree to which machines are employed to perform the work, i.e., the mechanisation rate. The greater the percentage of mechanised work, the greater the scope for automation. Improvements to the machinery may also be called for. In terms of mechanisation, individual machines may require modifications before automation can be applied on a larger scale.

3. *Is there any potential for minimising material losses?*

If loss of materials can be reduced or the required operation carried out using less material, financial gains may be made by improving the work procedure. In road construction, any savings that can be made in the materials used for the structural layers are highly significant. The potential for savings is determined by the price of the material - the higher the price, the greater the savings potential. Another possible source of substantial savings is the consumption of binders (such as bitumen, cement, etc.).

4. *Does automation improve the overall efficiency of the work procedure?*

This indicator is used to evaluate the work procedure as a whole. If the construction machine is the bottleneck in the process or serves as the basis for evaluating the required work input, automatic control will affect the entire process directly. Therefore the potential for automation is quantifiable. If, by contrast, the bottleneck lies somewhere else, the overall efficiency of a work procedure is not much improved by the automation of a single work operation, meaning that any benefits gained thereby are slight.

5. *Are the requirements for geometric accuracy essential in the work procedure?*

Accuracy requirements (tolerances) are often the underlying reason for efforts to increase automation. If these requirements are high, accurate measurements and control may be justifiable. More often than not, it is difficult for human beings to achieve the required accuracy with conventional work procedures. However, if the accuracy requirements are secondary, it is hard to identify any major potential for automatic control. As far as actual road construction is concerned, the required level of accuracy can be determined from things such as whether any levelling labels/rods are required on the site for alignment. As a rule, height accuracy requirements for roads are stringent (sometimes calling for absolute and sometimes for relative accuracy).

6. *Is the design data required for machine control available?*

Numeric machine control requires a model for such control. This indicator helps to evaluate whether the current design process generates the geometric and other data required for machine control. The data can also be obtained on site before or during the actual work operation. If such data is currently unavailable, the overall procedure needs to be developed in this respect as well in order to apply automation. If, by contrast, the data is available, it will facilitate the development and introduction of automatic control. If the design data is available easily or at low cost, automation will require less effort. Other important considerations in this respect include issues such as whether CAD is used for the design of the component or work operations, whether the data is available in electronic format and whether the design has been carried out in a 3D environment.

7. *How technically complicated is the implementation of automatic control?*

If automation requires extremely complicated technology, it is difficult, though possible, to gain financial benefits from automating the work procedure. This indicator is used to evaluate the need of 3-D control of machine, the level of competence required to control the machine (operator skills, number of "human sensors", precision control), feasibility of 3D positioning, functionality requirements, number of sensors required on the construction machine, popularity and reliability of the required control logic, number and/or level of latent uncertainties, operator's expectations as to benefits and other similar factors.

8. *Does the work procedure involve any tasks that are dangerous or hazardous to human health?*

One of the driving forces in automation is the desire to improve safety at work. This indicator is used to evaluate the number of dangerous operations (accident statistics, accidents resulting in injury or death). For example, deep excavations can be dangerous while machines, as such, may pose a risk to people. Other considerations related to this indicator include the level of "hardship" in work (harmful effects of impurities, – alveolar air, skin, clothing, etc.), amount of hard and enervating work (worn-out joints, overexertion, etc.), occupational safety aspects of machine manoeuvring techniques and workplace ergonomics as a whole.

9. *Does automation improve the competitiveness of the contractor?*

It is unlikely that automatic machine control systems will be introduced on a large scale unless they are financially profitable to contractors. This indicator is used to evaluate issues such as whether automation reduces the required work input (the greater the reduction, the greater the potential for automation), added efficiency provided by automation, level of required capital outlays (primarily the purchase price of automatic control technology relative to the purchase price of the standard construction machine and assumed increase in efficiency), the hourly rate and/or unit price paid to the contractor (if the price is low, the investment in automatic control does not pay off), whether it is a question of a strategic investment (no contracts awarded in the absence of automatic control systems), whether automation will replace some other work operation (such as automatic quality control measurements), whether the procurement policies and types of contract permit the purchase and operation of machines with automatic control, and the financial benefit of the investment to the contractor (benefit/cost, payback period).

10. *Does automation improve the standard of quality of road structures?*

One of the basic reasons for introducing automatic control is to improve the standard of quality or to meet the applicable quality requirements. In road construction, the main quality criteria include the immediate improvement in geometric accuracy as well as reduced segregation, improved compaction of the structural layers, reduced susceptibility to frost action, improved strength, reduced settling, extended service life and reduced need for maintenance.

11. *Does automation in road construction promote sustainable development and improve the state of the environment?*

Research on the environmental impact of road construction is expanding. However, there is little data on actual findings. For the purposes of this study, the "eco-indicator" is used to focus general attention on how automation affects the environmental impact of various work procedures and/or to what extent recycling is increased because of automation. If automation reduces energy consumption (because or the reduced harmful impact of the generation/use/transmission of energy) or decreases the need for transporting materials (in road renovation projects materials are ground and mixed on site without any need for transportation), this may be considered as offering added potential for automation in terms of the environment.

2.2 Field study

A straightforward method of evaluation was devised to carry out the field measurements:

1. *Identification of the work procedure*

The first step is to identify the most common working operations and procedures used on road construction sites (Sections 2.1-2.2), i.e., what it is that is done and how. Several different procedures may be used to achieve the same final result (product component). Work procedures may also vary according to the contractor.

2. Description of the work procedure

A description of the work procedure must be provided at least to the level of accuracy dictated by the indicators used for determining the potential for automation (Sections 2.1-2.2). Essential issues and factors include the following:

- method of input measurements and planning, tools
- construction machines and manual work procedures involved, percentage of human labour
- requirements for 3-D control of machines and blades, required operator skills, current problems
- materials to be used
- accuracy requirements (tolerances)
- work operations that are potentially dangerous or hazardous to human health
- price of machinery, contractor's profit margin, level of compensation to contractor
- effects of the work procedure on the quality of road structures, sensitivity, i.e., the level of impact
- environmental impact of the work procedure, environmental performance.

3. Measuring the potential for automation

The potential for automation is gauged using the indicators developed for the purposes of the present study (a special form for recording the results of field measurements is provided).

Scoring:

2 points if the presence of the property being measured is strong or exceptionally clear in the work procedure;

1 point if the presence of the property being measured is perceptible in the work procedure;

0 point no presence of the property being measured is discerned in the work procedure;

-1 point if there is a negative presence of the property being measured, i.e., an opposite negative effect is exceptionally strong.

4. Processing of the results of the measurements

Each work procedure is analysed specifically to each indicator and accompanied by a verbal description. The total points scored for each work procedure are added up. The greater the number of points scored, the greater the potential for automation.

Scale:

15-22 points the work procedure is highly suitable for automation which offers great potential for financial benefit

9-14 points the work procedure is suitable for automation which offers clear potential for financial benefit

3-8 points the working method is no that suitable for automation which offers little potential for financial benefit

-9…+2 points the work procedure is poorly suited for automation which offers no foreseeable financial benefit.

3. RESULTS

The scoring results of the examples grader, milling machine and excavator are presented in the tables 1-3.

When the superstructure of a road is built, the laying and shaping of the sub-base and load-bearing layer is usually carried out with a grader. The chain of work operations include a number of clearly identifiable tasks such as preparations, spreading and shaping of the material forward, reversing with the blade up, and finishing. Preparations and finishing also include relocation of the machinery. Essential in the operation of a grader is the correct adjustment of the spreader and shaper blade to match the geometry of the road. The number of measurements and adjustments required is very high. At the same time, the accuracy tolerances are tight down to ±20 mm in the vertical direction (load-bearing layer). With the 3D positioning technology and an automatic 3D model, it is possible to achieve a level of accuracy and efficiency that is beyond non-automatic systems. The potential for savings in terms of the required work input is great. A grader is used side-by-side with other road-construction machines, so that a successful sequence of machine operations is essential to the quality of the road structures. Graders are also used for winter maintenance which includes a number of specific tasks in which efficiency could be improved through automation.

Figure 1. Road grader – the reference.

The stabilising work operations designed to improve the structure of the road include preparations, initial planing, shaping of the layer and, if necessary, the addition of aggregate, stabilisation milling, and finishing. Stabilisation with bitumen (foam and emulsions) is the most common method of structural road improvement used on "low-grade" roads in Finland. However, further research is called for if a technically and financially sound automated stabilisation milling is to be achieved. Operations that could be automated included milling depth, angle of gradient, infeed of binder, infeed of additive (water). Final shaping and levelling is carried out with a grader even in stabilising milling.

Figure 2. Milling machine – manufactured in Finland.

The standard work operations included in excavation include preparations, intake of material in the bucket, turning and dropping the load, and finishing. The most common method is that of using the back hoe excavator. Controlling the position of the machine and all the 3-D control tasks calls for great expertise on the part of the operator. For example, maintaining the stability of the machine requires close control and adjustment. For an inexperienced operator, the work can be risky, even dangerous. In embankment filling operations, the excavator is used to shape and finish the structural layers and slope ramps in three dimensions. The angle through which the machines turns should be as narrow as possible. In cutting and embankment-filling operations, the requirements for geometric accuracy usually range from ±5 to ±10 cm and may be even greater for finishing. Thus, 3D control may be indispensable in finishing operations.

Figure 3. Excavator.

Table 4. Results of measurements to determine the potential for automation.

Machine	*Points*
truck	9
wheel loader - loading	8
wheel loader - finishing	13
caterpillar	12
road grader	14
gravel spreader	10
roller - compaction of unboud layer	12
roller - compation of bound layer	10
milling machine	10
excavator - cutting and embankment fillingt	10
excavator - finishing	13
pile driver	14
in-depth stabiliser	12
bulk stabiliser	10
rock auger	11
asphalt spreader	15

4. CONCLUSIONS

The results of the evaluation of the potential for automation of road construction machines using the indicators developed in the course of the study are presented in Table 14 as numeric values. This approach makes it possible to assess automation potential systematically. The method is described in this reports and may be used for prioritising future product development projects. If the grader analysed in this project is used as a frame of reference (see the observations and results obtained in field testing), a general evaluation of the potential for automation of other work procedures and construction machines can be made using this approach. The total number of points scored by the grader was 14.0, slightly higher than the average for all machines which was 11. (standard deviation being 2.0). Assuming that the indicators cover all the contributing factors extensively enough, it is safe to say that financial benefits correlate with the results of the measurements. Consequently, indisputable financial benefits may also be expected from the automation of other work procedures. However, the present study is probably not extensive enough to provide any unambiguous proof of the benefits of automation.

The study suggests that the greatest potential for automation is offered by machines used for performing tasks that require careful preliminary planning and great accuracy. These work procedures involve a lot of repetitive motions and fine adjustments. Such machines include the road grader and asphalt spreader, particularly when used for shaping and finishing the superstructure. At the same time, automation offers definite benefits in the laying of the road foundations which is an expensive and complicated operation because it enables improved management of the entire work process. The benefits are realised in terms of savings in the consumption of binders, improved quality of the final product or fewer broken piles. Needs for various levels of automation were identified for most machines and work procedures evaluated in the course of the study. One area where automation is called for on all construction machines is the collection of documentation and quality control data.

5. REFERENCES

[Heikkilä & Jaakkola] Heikkilä, R. & Jaakkola, M., 2002, The Efficiency of a 3-D Blade Control System in the Construction of Structure Layers by Road Grader – Automated Design-Build of Road Construction in Finland. ISARC'2002, 19th International Symposium on Automation and Robotics in Construction, 23-25 September 2002. Washington, DC, the United States of America, pp. 475-480.

[Heikkilä & Jaakkola] Heikkilä, R. & Jaakkola, M. (2003) Tienrakennuskoneiden automaattisen ohjauksen tarpeet ja mahdollisuudet. Osaraportti I, Tienpidon digitaalisen toimintaprosessin kehittäminen ja rakentamisen automatisointi. Oulu, Rakentamisteknologian tutkimusryhmä, tutkimusraportti, 56 s + liitteet.

Table 1. Analysis example: the results of measurements for a road grader.

Indicator	*Many*	*Some*	*None*	*Neg.*
1. Does the work procedure include any repetitive task?	●	○	○	○
2. Is it possible to mechanise the work procedure or has it already been mechanised?	●	○	○	○
3. Is there any potential for minimising material losses?	●	○	○	○
4. Does automation improve the overall efficiency of the work procedure?	○	●	○	○
5. Are the requirements for geometric accuracy essential in the work procedure?	●	○	○	○
6. Is the design data required for machine control available?	●	○	○	○
7. How technically complicated is the implementation of automatic control?	○	○	○	●
8. Does the work procedure involve any tasks that are dangerous or hazardous to human health	○	●	○	○
9. Does automation improve the competitiveness of the contractor?	○	●	○	○
10. Does automation improve the standard of quality of road structures?	○	●	○	○
11. Does automation in road construction promote sustainable development and improve the state of the environment?	○	●	○	○
points	*10*	5	0	-1
total points				***14***

Table 2. Analysis example: the results of measurements for a milling machine.

Indicator	*Many*	*Some*	*None*	*Neg.*
1. Does the work procedure include any repetitive task?	●	○	○	○
2. Is it possible to mechanise the work procedure or has it already been mechanised?	●	○	○	○
3. Is there any potential for minimising material losses?	○	●	○	○
4. Does automation improve the overall efficiency of the work procedure?	○	○	●	○
5. Are the requirements for geometric accuracy essential in the work procedure?	○	●	○	○
6. Is the design data required for machine control available?	○	●	○	○
7. How technically complicated is the implementation of automatic control?	○	○	○	●
8. Does the work procedure involve any tasks that are dangerous or hazardous to human health	○	○	●	○
9. Does automation improve the competitiveness of the contractor?	○	●	○	○
10. Does automation improve the standard of quality of road structures?	●	○	○	○
11. Does automation in road construction promote sustainable development and improve the state of the environment?	○	●	○	○
points	*6*	5	0	-1
total points				***10***

Table 3. Analysis example: the results of measurements for an excavator.

Indicator	*Many*	*Some*	*None*	*Neg.*
1. Does the work procedure include any repetitive task?	○	●	○	○
2. Is it possible to mechanise the work procedure or has it already been mechanised?	●	○	○	○
3. Is there any potential for minimising material losses?	●	○	○	○
4. Does automation improve the overall efficiency of the work procedure?	●	○	○	○
5. Are the requirements for geometric accuracy essential in the work procedure?	○	●	○	○
6. Is the design data required for machine control available?	○	●	○	○
7. How technically complicated is the implementation of automatic control?	○	○	○	●
8. Does the work procedure involve any tasks that are dangerous or hazardous to human health	○	○	●	○
9. Does automation improve the competitiveness of the contractor?	○	●	○	○
10. Does automation improve the standard of quality of road structures?	○	●	○	○
11. Does automation in road construction promote sustainable development and improve the state of the environment?	○	○	●	○
points	*6*	5	0	-1
total points				***10***