Automating excavators to reduce cycle times and maintain safety & accuracy

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\textbf{ABSTRACT}

The increasing cost and size of the excavator pontoons currently used by dredging contractors makes it cost-effective to invest in the further automation of these dredging machines. Most excavators in dredging are controlled by an operator, with back-up from a monitoring system using a DGPS (Differential Global Position System) to track bucket movements. Extensive systems are required to ensure that the scheduled bottom profile conforms with the dredging contract and/or the quality control system of the principal. In general, the required dredging accuracy is 10 cm.

Experienced operators using the DGPS coupled monitoring system will have a good mental image of where soil still has to be removed, and where the next dredge bite is required. They are very familiar with the machine and they can steer the dredging sequence to maximise efficiency. However, experienced operators may be harder to find, and even they can get tired, distracted, or possibly even bored. These are all accepted factors that can prevent the most efficient use of the excavator.

Rapidly switchable full automation to control all the movements of the excavator and automatically dig a multi-cycle pattern will be a major improvement in the dredging world. This is a logical step forward against the backdrop of earlier automation of other common dredging equipment such as hopper dredgers, cutter dredgers and bucket dredgers.

An automatic excavator can guarantee a given cycle time. This may be slightly longer than the cycle time of an alert and experienced operator, but it will be shorter than the cycle time of an inexperienced, tired or distracted operator. An automated excavator can therefore improve production figures. In loose soil types, indeed, this improvement can often be guaranteed, as has been confirmed by initial experience. And, at the same time, a close watch can be kept on safety and accuracy.

In this way, the dull repetitive part of the excavation process is handled by the computer, and the more interesting tasks like planning and improvements in the dredging process are left to the operator, while reducing cycle times, and therefore making operations more cost-effective and making the operator's work more ergonomically friendly.

This paper describes the challenges that were encountered and resolved in the man-machine interaction.

\textbf{INTRODUCTION}

Before going into general use, most new technology is developed for and tested on specific projects. Excavator automation was tested on one of Germany’s largest dredging projects: the Jade Weser Project. The Jade Weser Port is working on the construction of a deep sea container port. A large land reclamation project has started, in combination with dredging to make the waterway suitable for large container vessels. The Jade Weser Port is located in the Jade Weser estuary, which is part of the German Wadden Sea, approximately north-west of Bremen. The Wadden Sea is a shallow sea where the tide plays a predominant role, generating large currents in the deeper trenches that run through the mud flats. The soil is partly sandy, partly heavy silt. There are also occasional bombs left over from the Second World War. Strict environmental rules for any activity prevent unnecessary damage to the sensitive area.

The Jade Weser Port is located in the trench of the Jade, and the water from the Jade Büsen runs through this trench twice per tidal cycle. This results in currents of up to 5 knots, 4 times a day. For a dredging project that also involves the use of excavators, these are quite dynamic conditions which affect the possible size of the dredging machines to be deployed. In general, relatively small cutter dredgers or excavator dredgers will have fewer working hours than larger ones due to weather conditions.

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The Jade trench will be deepened with one of the largest excavators on a pontoon, the Liebherr 995. The excavator is a huge machine designed for dredging and mining and, with the pontoon and associated barges, it represents a major capital investment. The machine is a standard product from Liebherr, but the boom and stick are longer so that it can reach farther and deeper. The pontoon normally floats during transport and positioning. Just before dredging starts, it is lifted up on three spuds to create a stable platform.

The MP40 pontoon with the Liebherr 995, with one barge alongside and one barge approaching

At present, the operator of a dredging excavator works from the cabin on the excavator, a rather limited space filled with equipment for controlling, positioning and monitoring the excavator. Since this kind of capital investment has to work efficiently and to accuracies that exceed mandatory levels several times over, the underwater nature of the work means that operators have to rely on their monitoring equipment. Without this equipment, it becomes extremely difficult to work and to track the digging job on the sea floor or river bed.

The operator is in a “moving” environment during the process. Most of the time, operators are engaged in repetitive work as the excavator machine digs and rotates, causing continuous strong vibrations. By comparison with other working environments, this is a sort of “worse-case scenario” in terms of working conditions. Fatigue and accidents, resulting in inefficiencies and extra costs, are always just around the corner.

The management is well aware of this and so there is an automatic interest in maintaining safety and efficiency for the whole operation, and particularly in optimising the operation of large excavators by helping operators to work safely, efficiently and accurately.

PROCESS DESCRIPTION & THE HISTORY OF OPERATOR EQUIPMENT

During the 1970s, many people involved in dredging were prepared to work with human imagination rather than insisting on accuracy. Even when the bucket is above the water, it is still hard to envision the position of the bucket accurately. This means that the distance between the operator and the bucket cannot be estimated by sight alone. Below the waterline, this may impact efficiency: digging in the wrong place, for example, or at the wrong depth. Alternatively, because of the importance of accuracy, the dredging process (i.e. the cycle time) will be slowed down considerably.

However, the impact of other estimation errors above and below the waterline may even be more costly. The excavator may damage the pontoon or the barge with the bucket below the waterline, and they may even sink as a result. Although this is not perceived as a serious hazard with relatively small excavators and barges, it is for huge excavators with an extended boom and stick. This risk generates severe mental strain that can result in operator fatigue, with a negative impact on safety and efficiency.
For example: deepening trenches in waterways is, by definition, performed below the waterline. The task of the operator is repetitive and tedious but the dredging forces and the potential for damage make operator concentration mandatory. The mental burden on the operators is therefore high. To keep track of the job, excavators often have equipment on board to visualise the position of the bucket, boom and stick and to keep track of progress, and prospect. This makes things easier since operators no longer have to remember where they have been and it reassures that the job will continue satisfactorily after operator changeovers. Most pontoons have two crew members who switch jobs several times during the day.

All this has convinced a number of dredging companies that the monitoring and automation of several functions on the excavator can be beneficial for production.

Even though no one in the field thinks automation can outperform experienced operators over short periods, automation continues to perform at exactly the same level as at the outset, whereas operators have more difficulty in maintaining concentration and performance over time.

These facts are proven by the widespread use of both monitoring systems and the automation of certain hydraulic functions of the excavator:

- **Automatic swing limitation**
  Limits the hydraulic swing drive when the tool reaches a pre-programmed position, preventing extreme forces on the excavator’s rotation mechanism.

- **Automatic outreach limitation**
  Based on the calculations of a monitoring system, this system controls stick movement in the outward direction when the excavator reaches its maximum outreach line, ensuring a smooth stop.

- **Automatic pontoon damage limitation**
  Limits or stops the inward movement, preventing pontoon damage.

- **Automatic profile/depth dredging (automatic boom steering)**
  This automation facilitates faster operation for accurate slope dredging by controlling the position and speed of the excavator boom. The operator can concentrate on controlling the stick and the tool, and the automatic action will make the tool follow the dredging profile accurately.

- **Bucket automation**
  Maintains the bucket teeth at a pre-defined angle to the dredging profile. In hard soil, this benefits the continuous application of the maximum cutting force and improves the production rate and the working accuracy, while reducing cycle time.

- **Spud step automation**
  Provides an automatic step facility for the spud carrier.
The men and their mighty dredging bucket

The automation systems mentioned here all had to resolve the problem of adapting electronic hardware and software to the excavator’s hydraulic system. This challenge was resolved in the course of time. Advances in computer power and smarter hydraulic installations were decisive factors in progress towards devising appropriate automation.

Another preliminary step towards safe, accurate and reliable automation was the development in 1998 of “memory steering” for a KOMATSU DEMAG 185 excavator. This step allowed operators to execute a certain movement and then repeat it as often as they liked with the help of record/replay push buttons. However, the step to automatically dredging a profile and the incorporation of the barges’ position alongside the pontoon could not be handled by the PC platforms available in 1998. Furthermore, several hydraulic issues still had to be resolved to allow the excavator automatically operating at full speed.

At the Möbius dredging company, crew members and management had achieved interesting results. Even when operating semi-automatically under the constraints mentioned, the production rate was still significantly higher, justifying the attempt to move ahead with the complete automation. Innovation is a high priority at Möbius, facilitating quick set-up, testing and fine-tuning. And there is a consciousness that this kind of development is always a gradual process with the emphasis on safety, ergonomics, and reliability and operators’ trust.

The final step towards the newest excavator automation was the development and production of dredging simulators, especially an excavator simulator for Jan de Nul. The dredging world is making enormous efforts to improve dredging training with hopper simulators, cutter simulators and excavator simulators. This is a unique opportunity to combine the intellectual capital from various fields of dredging and simulate the behaviour of machines like excavators.

In conclusion, the dredging world has gradually accepted the monitoring and automation of excavator dredgers as part of widespread investments in efficient and accurate dredging. In many cases, work tolerance will be +/- 10 cm, to be confirmed by a post-dredging survey or by divers. In fact, some projects could not take place - or even be allowed - without monitoring of the process by a DGPS-supported eXcavator Position Monitor (XPM).
The key to safe automation is simulation ........

FROM OPERATOR TO PRODUCTION MANAGER

With managers far away on shore, operators are alone in their cabins. There is no good way to get them to use the automation systems unless those systems have something to offer: enhance their abilities but don’t replace them. So operator perception places certain design constraints on automation systems. For example, it took a while before operators accepted that what they were seeing on the monitors was true, and also to realise that possibly human errors were involved when something on the screens seemed wrong.

Mathematics to determine accurate bucket tooth position
First of all, operators have to remain in control. They can see more than sensors can measure and a monitoring system can display, and they can react to the unexpected. So the transition between manual and automatic operation has to be smooth. For that reason a pedal was introduced in the cabin, the sole additional control means for activating the automation systems. The pressure exerted on the pedal determines the maximum speed at which the automated system moves the excavator. When the operator steps on the pedal, the excavator operates automatically. However, as soon as he touches the control levers, the automation stops and control over any movement is returned to himself. So operators' reflexes and their train of thought will not be affected. They can move the excavator whenever they wish without having to execute difficult actions: the automatic system does not interfere with operator intentions. At his will it moves aside gracefully and, when he steps on the pedal again, the automatic system resumes operation. This concept was developed and tested on an excavator simulator and finally assessed to be favourable by three operators of different ages.

The dredging job can be broken down into a bite pattern, a plan for dredging a certain area efficiently. Operators use these plans to make sure that they don't miss any part, guaranteeing that the end result is at depth without any bulges. Dredging can start and stop for all sorts of reasons that are known to the operator but when the automation starts, it doesn't know for sure where to begin and to end. It requires a pre-programmed bite pattern that tells it where to place the bites as well as an indication where to dump the soil, while not knowing where the barge is alongside the pontoon.

The solution is to use artificial intelligence, noticing how the operator dredges: the system monitors his work and estimates where the operator is moving the bucket in the bite pattern and above the barge. After this estimate, the automation can determine fairly accurately where to continue, and whether to move clockwise or anticlockwise. After the estimate, the system informs the operator that it is available to start and the operator can decide when to use it or not.

If the work is repetitive and tedious, the operator can let the system operate independently for quite some time. If he wants to regain control, he simply uses the control levers, similar to the cruise control in a car. So the operator is relieved of the tiresome and repetitive bite-unload sequence. And can keep the mental burden at a comfortable level.

Automation exerts an inherent pressure on shifting operators to adopt a more uniform working method: the machine always takes over in the same way. This is exactly the kind of feature liked by managers, because it makes the whole job more predictable.

The conclusion is, that the operator on an automated excavator is moved slightly out of the immediate control loop, becoming more of a process operator – however limited: the technology is still not adequate to allow operators to leave the cabin and to work from remote. On the other hand, their capacity is greatly enhanced in terms of generating continuous high outputs at high accuracies. So these 'workmen' are now transforming into highly efficient underwater landscaping engineers.
THE SAFETY CHALLENGE

If something happens to the operator during automatic movement of the excavator, the excavator may continue uncontrolled. In that case, there will be no one to monitor safety and so a virtual environment was created as a safety aid and protection. The figure shows the volume in which the excavator is acting. It consists of a large volume above the dredging area, a smaller corridor, and the area above the barge. While the excavator is in these areas, the automation can move safely; if, for some reason, the excavator moves outside the safe areas, the automation stops. The protection feature is independent of the controller that determines how the boom stick and bucket move. This 'permitted volume protection' also verifies the manual operations of the operator as well.

Since it is a separate feature, it is relatively simple, while the automation still uses complex algorithms. It utilises reference points on the most outward parts of the excavator. The ‘permitted volume protection’ system monitors the position of these points and reduces the probability of error. It therefore also reduces the mental burden on operators during manual control. It also allows to program more complex algorithms for the automatic system without compromising on safety. The result is an excellent trade-off between safety, efficiency and excavator speed.

The icing on the safety cake is the automation pedal mentioned before. It is difficult for anyone to get onto a moving excavator and into the cabin to help the operator. In fact, it is prohibited for safety reasons to approach a huge moving object like an excavator. In effect, then, operators cannot be reached unless someone takes the risk of jumping onto the moving machine. So there has to be a means to determine whether an operator is still alive and conscious. The pedal is. It allows the machine to operate at full speed when it is pushed down for the largest part. The remaining pedal travel functions as a dead man's switch. As long as the operator moves the pedal up and down, the system is informed that he is still in control. In addition, if the operator takes any other action, the system will registrate and reset the dead man's timer. So far, excavator operators considere this a safe and ergonomic solution.

The larger excavators, used in dredging, are dangerous moving machines requiring permanent attention of all people in the neighbourhood to prevent hazard. For this reason a FMEA (Failure Mode and Effect Analysis) was conducted to obtain reassurance and a clear picture of the possibly changing safety status of the automation system.

This analysis indicates that the XPM (eXcavator Position Monitor) & AXC (Automatic eXcavator Controller) combination does not significantly exacerbate risks and hazards that are not already inherent in the design and use of the machine. At most, the XPM/AXC can be said to highlight the shortcomings more prominently than if the excavator had not been automated. Surely, the XPM/AXC is no risk-free approach: the combination of the excavator design and the automation represents a genuine challenge to maintain at least the existing safety level.

On the basis of observations during the commissioning period, the authors wish to emphasise that remedies are needed to maintain operator alertness. This is primarily a task for the machine owner and the operator. On the basis of the FMEA and brief experience in practice, several situations were improved indeed. But the final safety remains, as with any other machine, the responsibility of the operator and his awareness and understanding of the process he is running. As usual, the FMEA document does not consider cases of force majeure such as e.g. sabotage.

In conclusion, the XPM/AXC combination looks to be a useful automation tool that offers some extra safety at the one hand, and does not amplify the security issues that are always connected with such heavy machines at the other hand.
Accuracy and efficiency are closely related in dredging operations. Dredging contracts usually specify accuracy, and contractors usually express efficiency as the number of cubic metres dredged in the shortest time. With excavators, this comes down to the lowest possible average cycle time per bite. It also requires having a barge alongside, at any time so that the dredging work is not interrupted. One factor underlying efficiency is the mental burden on the operator, who has to maintain concentration. Over the past 100 years, a host of studies in all kinds of industrial and military contexts have established a clear picture of human performance, endurance and motivation during jobs with a relatively high level of repetition.

The two graphs above show the performance of a human as a function of mental load and task duration: It can be concluded that an operator without automation support has a higher peak performance than an automation-supported operator. On the other hand, a non-supported operator will see his performance worsen over time, while an operator, assisted by automation will maintain the same level of performance. These graphs suggest that a choice has to be made between the two, but in fact it is possible to have the best of both worlds by allocating the boring tasks to the automation. Just that allocation keeps the operator alert for the challenging moments when skills are really needed.

In this ideal situation, a more appropriate performance graph is the one here. The automation deals with the repetitive tasks at a constant performance level. If performance is defined, for example, as production/task difficulty, performance will be higher during events requiring peak concentration. The way to achieve this ideal is to integrate the automation seamlessly in the dredging routine of the operators. Clear demarcation is also required between the automatic systems’ and the operators’ tasks. The main issue is that responsibility for, and safety of the job does not rest with the machine itself or the automatic systems, but, as always, with the operator.

This automation required an ergonomic approach that would allow surveyors and operators to execute ever more complex dredging jobs without a lot of time-consuming data handling and adjustments to the dredging profile or lengthy preparations before the job can even get started. Therefore pre-programmed self-learning was introduced, to identify the working method and to combine this information with the movement of the excavator that was likely to be most efficient within the dredge pattern. Basically, dredging data is obtained from the survey department and put into practice by the excavator operator and the dredging job surveyor.

So the automation observes the operator first for a while. Processing the data by artificial intelligence, the system decides where to continue in the dredging pattern. This behaviour ensures that the operator can do his usual job: controlling the excavator well. When he decides it appropriate, he starts the automation. His actions will be noted, and the system carries on from that point without the operator needing to do anything else other than press the foot pedal. Even if the operator did not dredge exactly according to the pre-determined bite pattern, the automation adjusts accordingly and still tries to reduce the travelling time of the bucket. Even if the operator engages in some complicated manoeuvre to dig out obstacles like large rocks, the automation system feeds back information for de-
ciding about the position of the next bite when activated again. Such a situation, occurring at trench deepening in a homogeneous river bed or sea floor, can be handled by the automation.

Following the actions on the eXcavator Position Monitor

Horizontal bucket approach

Intersection of a bite with a flat bottom profile

Vertical bucket approach

Intersection of a bite with a flat bottom profile

Although the automatic systems can be set to dig vertically, the operator still has to check whether this is beneficial with the type of soil in the area. In some situations dredging will result in rounded corners as shown in the picture above (right). The system was designed to quickly excavate large volumes, and it will not dig below the desired end bottom profile. The implication is that certain precise tasks should still be left to the operator. Complex bite shapes, often required by environmental dredging can be done by the automation. It ensures that no more than the required soil will be removed. After removal of the bulk of the soil, a final stage can deliver cleaning up and the specified depth accurately.

The sloped type of bottom profile is typical for digging or deepening of canals. This type of work demands high accuracies, especially when the dredged profile has to be covered with some kind of protective layer like clay or gravel afterwards. The automation maintains both accuracy and speed without tailing off over time. The operator can focus on planning and optimising the bite patterns, with the automation performing them exactly as required.

Any profile that can be dredged manually, can be dredged by the automation. For example, at the removal of polluted material it may not be desirable to deliver a flat profile. A flat profile might just imply removing more material than the customer pays for. The automation automatically adjusts the bite pattern to that and will not dig deeper than required.
The excavator can perform bite patterns, consisting of shallow bites, in a single run. If, however, the soil volume in a bite is larger than the bucket volume, the excavator will stop in time to unload the fully loaded bucket. After unloading digging is resumed the same pre-programmed bite until that bite is fully completed. The bucket is unloaded as often as necessary to complete the bite.

The usability challenge

It is crucial that the operator has a good mental picture of what the automation will do. Therefore, the system must consistently show similar, predictable behaviour, and inform the operator about what it does. The excavator position monitoring equipment was extended to show the status and planned actions of the automation. It observes the operator during manual dredging, collecting all the information, needed for automatic operation, viz (see figure below):

- the position in the dredge pattern,
- the unload point or area ($P_{\text{discharge}}$),
- the positions where the bucket moves over the side of the barge (other legends in figure).

The operator can always interfere if an extra cleanup bite is necessary, or if there an anomaly (like a large stone) appears in the routine. If manual digging restarts the normal dredging sequence after that – which will often be the case – the operator can turn on the automatic system again to immediately resume operation. If he disagrees with the ‘plan’ of the automation, he can learn it one or more additional bites, until it reacts appropriately.
CONCLUSION

The automation of a large excavator like the Liebherr 995 is possible by focusing clearly on the task of the operators, and through the seamless integration of the automation with that task. This paper has discussed the challenges encountered and how they have been resolved to make excavator automation a successful improvement in excavator dredging. Surprisingly, the regular interaction between automation and the operator has the benefit of maintaining operator skills, and so the art of dredging remains with the true artists - the operators.

REFERENCES
