AUTOMATED EXCAVATOR, FIRST EXPERIENCES IN GERMANY

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ABSTRACT

The rising cost and size of excavator pontoons currently in use by dredging contractors, makes it cost effective to invest in a further automation in these dredging machines. Most excavators in dredging are controlled by an operator, assisted by a monitoring system supported by DGPS (Differential Global Position System) that keeps track of where the bucket has been. Extensive measures have to be taken to be able to guarantee the targeted bottom profile will be delivered in accordance with the dredging contract and the quality control system of the dredgework principal. Nowadays a required dredging accuracy of 10 cm (4 in) is commonly accepted.

Experienced operators, assisted by the DGPS coupled monitoring system, are able to keep a good mental image of where there is still soil to be removed, and where the next dredge bite must be done. They know the machine they operate well, and can steer the dredging sequence in a way that maximizes efficiency. However, experienced operators may be more hard to find, and even they will eventually get tired, distracted, or maybe even bored. These are all recognized factors that hamper the most efficient use of the excavator.

The introduction of quick switchable full automation, to control all movements of the excavator and automatically dig a multi cycle pattern, promise a great improvement to the excavator dredge world. It is to be considered a logical step ahead when comparing the backhoe to other, earlier automated commonly used dredging machines, such as hopper dredges, cutter dredges and bucket dredges.

An automatic excavator can guarantee a certain cycle time. Perhaps a bit longer than the cycle time of a fresh and experienced operator, but faster than the cycle time of a inexperienced, tired or distracted operator. Therefore an automated excavator can and will improve the average production rate. In looser, not too compacted soil types this improvement can often be guaranteed, as first experiences have confirmed. The automation developed and tested can do the full cycle, while keeping a close watch on safety and maintaining accuracy, all at the same time.

This way the repetitive part of the excavation process is handled by the computer, and the more interesting tasks like planning and dredge process improvement, are left to the operator. Achieving as well a lower cycle time, and for this more cost effective operations, as a more ergonomic friendly task for the operator.

This paper describes the first practical experiences in 2010, in Germany.

Keywords: Mechanical Dredging, Automation, Artificial Intelligence, XPM, Jade Weser Project Germany.

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INTRODUCTION

The Jade Weser Port in Germany is constructing a new deep sea container port one of Germany's largest dredging projects: the Jade Weser Project. In combination with dredging to make the waterway suitable for large container vessels also a large land reclamation project has started,. 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 characterized as a shallow sea, where the tide plays a dominant role, generating large currents in the deeper trenches that run through the mud flats. The soil is partly sandy, partly heavy silt. Occasionally bombs or mines from the World Wars are encountered. Strict environmental rules for apply to prevent unnecessary damage to this 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 can result in currents of up to 5 knots, 4 times a day. For a dredging project that also has selected the use of excavators, that current reflects quite dynamic conditions, which affect the possible selection of size of the dredging machines to be deployed. In general it can be stated that here relatively small cutter dredgers or excavator dredgers will have fewer working hours than larger ones due to the local environmental conditions.

Figure 1 shows the commonly known specifics of the German Jade Weser project, including the common excavator instrumentation and automation of these last years.

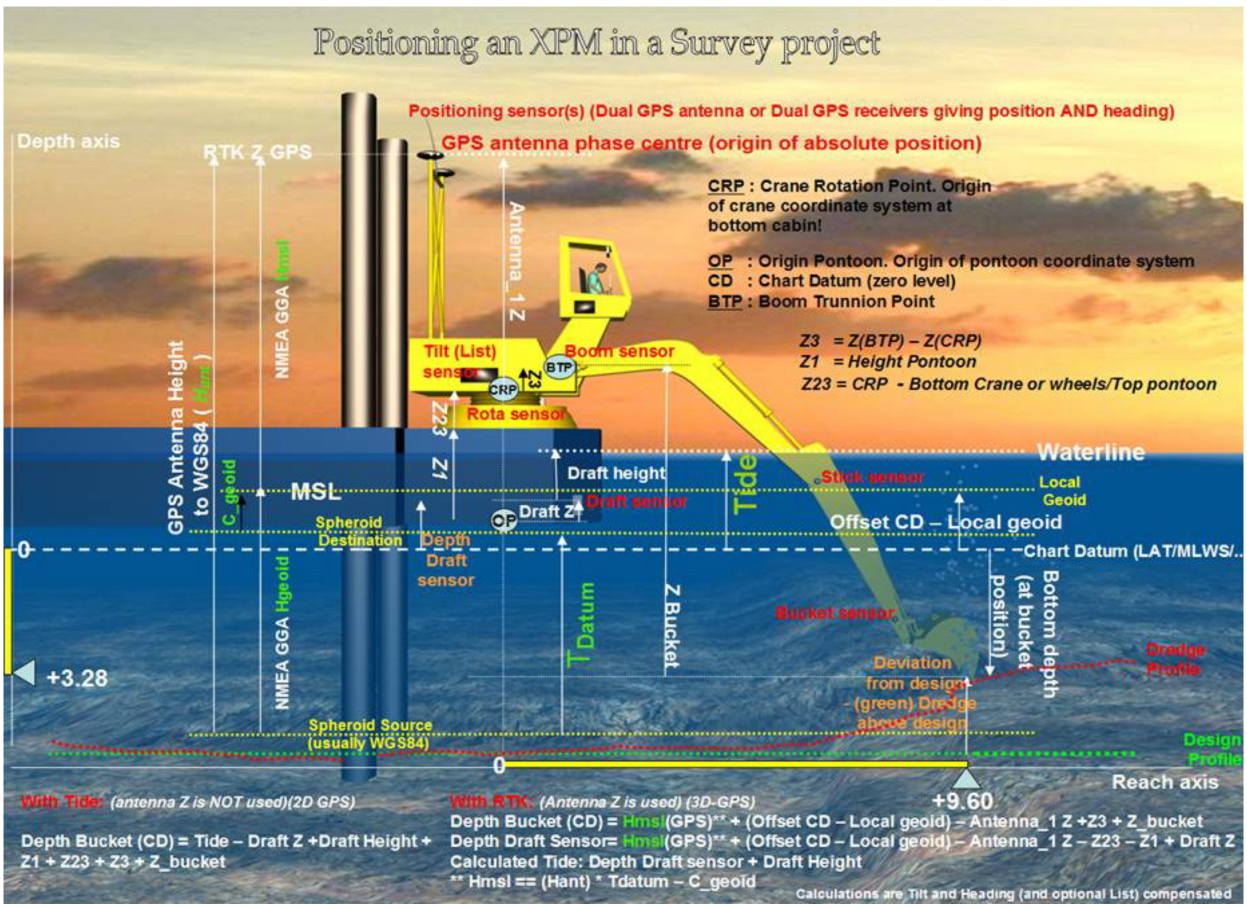

Figure 1. Mathematics to determine accurate bucket tooth position.

The Jade trench is among others deepened by one of the largest excavators on a pontoon, a Liebherr 995 backhoe (Figure 2), accompanied by barges. The tool combination represents a major capital investment for the dredge company. The Liebherr 995 excavator is a basically a standard product from Liebherr, with custom built boom and stick, to reach farther and deeper with these lengthened components. The pontoon normally floats during transport and positioning. Before dredging starts, the pontoon is jacked up on three spuds to create a stable platform to withstand the excavating forces created and encountered.

Figure 2. The MP40 pontoon with the Liebherr 995, with one barge alongside.

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 within accuracies without acceptable over-depth allowances, means that operators have to rely on their monitoring equipment for this invisible underwater. Without such instruments, it would become extremely difficult if not impossible, to perform that work, leave alone 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. Comparing this excavating work with other working environments with excavators, these working conditions represent a sort of “worse-case scenario. Further, the dredging cycle of this mechanical dredge process, is repetitive. Boredom and fatigue do create risks to consequential accidents and are a realistic exposure to be evaluated. Extra costs are often reserved.

The management is well aware of such considerations. There is an clearly expressed interest in maintaining safety and efficiency during the whole operation. Particularly an interest in optimising the operation of large excavators is often relayed, by checking the possibilities to provide help to operators to work safely, efficiently and accurately.

After describing the size and circumstances of the Jade Weser project, it will be no surprise that the owner of the large (Figure 3) Liebherr 995 backhoe in this project in was interested in automation.

Figure 3. The man and his mighty dredging bucket.

The Liebherr 995 was therefore equipped with the latest excavator automation and was, after commissioning, extensively used during the actual work performed.

PROCESS DESCRIPTION & THE HISTORY OF OPERATOR EQUIPMENT

It lasted throughout the 1970s, that many involved in dredge operations accepted and were prepared to execute dredge jobs using human imagination rather than insisting on accurate measurements. That is a difficult task with a backhoe: even when the bucket is above the water, it is still hard to envision the position of the bucket accurately. The hard conclusion is that distance between the operator and the bucket cannot be established by sight alone. Below the waterline, this impacts efficiency. For instance: digging in the wrong location or depth. In addition, due to the pressure on accurate performance, the cycle time in this dredging process 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 below the waterline with its bucket, even risking sinking as a result. Although this is not perceived to be a serious hazard when working with relatively small excavators and barges, it has proven to be a real risk for large excavators with an extended boom and stick That risk has shown to be able to generate severe mental strain, which contributes to operator fatigue, with a negative impact on safety and efficiency.

For example: by definition deepening trenches in waterways is performed below the waterline. The dredging forces and the potential risk of damage, requires a high level of operator concentration. The task of the backhoe operator is repetitive but tedious. The mental strain on these operators can be high. To assist them with means to visualise the task, excavators are nowadays often equipped with instrumentation to picture the position of the bucket, boom and stick and to keep track of progress, and project. That simplifies a part of the job of the operators, as they no longer have to remember where they were digging and to what location to return the bucket. It also is a tool to simplify proper task transfer during operator change-overs. (Most backhoe dredgers apply two crew members who alternate jobs several times during the day.)

Considerations as the above, have convinced a number of dredging companies with backhoe dredges that further monitoring and also automation of several functions on the excavator can be beneficial for a better production.
An important early step towards safe, accurate and reliable backhoe dredge automation was the introduction in 1998 of "memory steering" for a Komatsu Demag 185 excavator. This development 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 automatic dredging of a certain pre-programmed 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 interfacing discrepancies still had to be resolved, before the excavator could operate automatically at full speed.

Even though no one in this special field thinks that automation can out-perform an experienced operator over a short period, it is accepted that automation will continue to perform during a longer period at exactly the same level as at where it started, whereas operators have shown to be regular humans, suffer after a more or less time of fatigue, have more difficulty in maintaining concentration and show a reduced performance over a longer period of time.
Those statements have been proven to be a fact by widespread practical experience with both monitoring systems and levels of automation on certain hydraulic functions of the excavator. During the last 15 years different partial automation steps have been developed and added to the position instrumentation. These automations steps included:

- *Automatic swing limitation*
Limiting 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 of the bucket/stick, preventing pontoon damage.

-*Automatic profile/depth dredging (automatic boom steering)*
This automation step 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 automation controls 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 automation systems listed above, all faced the challenge with every other excavator and its dedicated hydraulic to develop an electronic hardware and software interface for that particular execution. These challenges were resolved in the course of time. Advances in computer power and options and hydraulic installations in the excavators applying "smarter" controls were decisive factors in the progress towards developing useful automation steps.

An important factor for in this type of development is always that a number of dredging companies and machine manufacturers support the challenge and joined the effort to contribute to step forward in such a specific area. As we all know, dredging requirements, equipment and circumstances can differ highly and to make progress in such a specific area, it is important to agree to "universal" base for solutions and not to a "one trick pony". The target is always to submit finally a solution that can be applied on a larger part of the dredging work in the world-wide dredging market.

The Möbius dredging company in Germany, crew members and management had achieved interesting results with the automation steps already made available during the last decade. Even when operating in semi-automatic mode under the constraints mentioned, the production rate in semi-automatic was still significantly higher than when operating manually. That fact was for this company the justification to attempt to move ahead with a step towards complete automation of the backhoe dredge cycle. Innovation has been a high priority at the Möbius company, facilitating quick set-up, testing and fine-tuning. The company was conscious of the fact that this kind of development is always a gradual process and puts the emphasis on safety, ergonomics, and reliability and operators' trust.

Also in the United States several semi-automation functions were extensively tested on various dredging projects. A good example was the instrumentation and automation installed in 2006 on the Komatsu PC 3000 on the Megan Renee pontoon of J.E. McAmis (Figure 4). All available technology was installed on this machine and applied, depending on the dredging requirements in their different projects. Together with the Liebherr 995 & 996 this kind of huge excavators have been selected for many dredging projects in the United States. Dredging companies including Donjon Marine Co., Great Lakes Dredge and Dock Company (GLDD) and Jay Cashman, Inc. all built there own extensive experiences with the monitoring, positioning and automation of the hydraulical functions of this kind of excavators. To utilize these backhoe dredges efficiently, they have created a separate class of dredge machinery, including the necessary logistic support of barges, tug boats and other auxiliaries as far as required investments.

Figure 4. The MEGAN RENEE and her KOMATSU C 3000

Compared to the overall world dredging market, the dredging market of the United States can be characterized by the relatively large amount of "special projects", involving excavators as the principal dredging machine. This brought also companies in this field such as the Washington Group-Alberici (WGA) Joint-Venture on the new

Olmsted Dam and Sevenson Environmental Services Inc. with several environmental dredging projects, to use the excavator dredging technology for digging as as well other tasks, for instance placing gravel and/or stones. In all of these types of jobs, the availability of different automation levels proved to be a determining success factor. In a number of specific, special task dredging jobs it would have been either impossible or very expensive to realize the required level of accuracy for the dredging and/or construction part without proper positioning and monitoring instrumentation and the automation of certain hydraulic functions. The development of backhoe instrumentation and steps of automation into a full automation includes therefore a development of the combined experiences in Europe and the United States of America.

Today it can be stated that gradually the dredging industry has accepted the monitoring and automation of excavator dredgers as a necessary investment to be able to dredge in a competitive environment efficiently and accurately with a backhoe dredge. In many cases, the completed work tolerances will be defined to be +/- 10 cm (about 4 inches) , in the permit, to be verified by a post-dredging survey or by divers. It has gone so far that some backhoe dredge projects are not allowed to start without the verified capability of the dredge to monitor the dredge process by means of a DGPS-supported eXcavator Position Monitor (XPM).

The latest step towards creating the newest excavator automation was the development and production of dredging simulators, especially an excavator simulator for Belgian dredging contractor Jan de Nul. The dredging world is making substantial efforts during the recent years 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.

LEARNING BY ARTIFICIAL INTELLIGENCE

The complete dredging job of the backhoe can be broken down into a pattern of sequential bites, reflecting the total plan to dredge a certain area efficiently. Operators use such a plan to make sure that they do not miss any part, guaranteeing that the end result is at targeted depth without any left bulges. Dredging can start and stop for all kind of reasons that decided by the operator for reasons decided by him, however when the automation starts, it does not know 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 positioned alongside the pontoon.

The solution was found by applying artificial intelligence, recording how the human operator executes his dredge task. 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 and how to continue, and whether to move clockwise or anti-clockwise. After the estimate, the system informs the operator that it is available to start and the operator has than the option to decide to use the fully automatic mode or not. If a specific dredge job is a tedious and repetitive task, the operator can let the system operate independently for quite some time. If he wants to regain control, he simply uses the control levers, in a similar way as the cruise control in a car is disabled. This relieves the operator of continuous handling of the repetitive and tiresome underwater bite-unload in barge sequence. The mental load is reduced to a more 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 contributes greatly to make the complete job more predictable. However in this project that specific assumed benefit was catalyzing a great deal of discussion about the different dredging methods possible and available, of course culminating in the most important question for this project: what will be the best dredging method with an excavator on a pontoon. Many issues were evaluated, including operator personalities, and advantages weighed against disadvantages. It is vital in this type of decisive strategic discussions is to have sufficient input. In reality this proved to come down to a lot of discussions between different software engineers and different pontoon operators.

The role of a simulator proved to be very decisive in this process of determining what the best way of operating would be from an ergonomic point of view. The simulator had the ultimate benefit it is relative cheap and very safe equipment to try out all kind of ideas for a longer period of time with a host of people. The automation must not only function, but it must also be appealing to use. Resistance to the concept by adding additional tasks, like involving the operator’s hands who may already be busy with other things, or have to be made free in order to be able to take over manually - creating overload- were intentionally avoided. By the time, the final choices had to be made and technology to be implemented on such a multi-million dollar machine, there was a clear, well documented decision why the path had been followed in a certain way.

Final discussions were held around the excavator simulator (Figure 5) and, most important, accepted by all people involved. This way of development made the final result also a teamwork product. It created a common interest of all people involved to make the best out of this automation concept. Logic prevailed over emotions. Some staff involved changed their dredging behaviour. Not because of pressure exercised, but the illustrated and documented process also involved a positive learning process, stimulating a generally accepted common sense. The fact that each one involved felt committed and wanted to achieve the best possible result was a large stimulus for general acceptance.

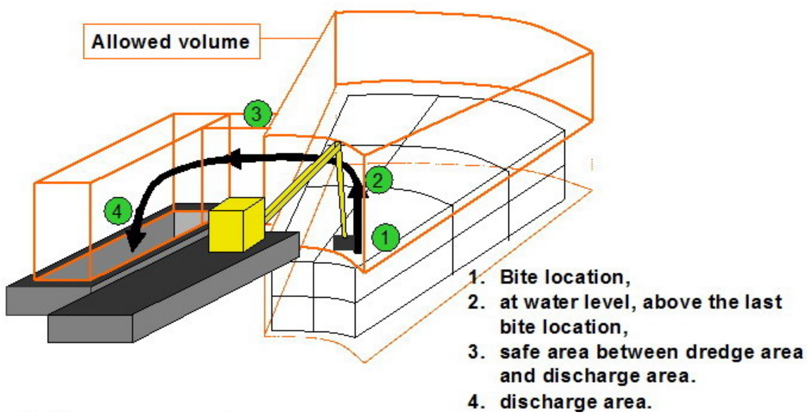

Figure 5. Definition simulator environment.

A typical side effect with an automation project dealt with in this fashion, is that all those involved started to realise that a term like Artificial Intelligence (A.I.) is not an abstract term for a far distant future in laboratories, but it is here and now available, also to help improving dredge productivity. The way A.I. is functioning and applied, can be influenced, by personal input of the operator with a good set of arguments. It is self- learning concept, but the operator determines how it is learning and how it will behave.

AUTOMATION EXPERIENCE OF THE USER

We learnt there is no good way to get operators to use the automation systems unless those systems have something to offer: Enhance their abilities but do neither pretend nor intend to replace the human. It is extremely important to realise and express clearly that the largest benefit is in a combination of man, machine and automation. We all experience the same conclusion in many other industries and our personal life, from medical interventions to driving our cars.

First of all, the operator has to remain in control. Do not deny that human factor will remain a necessity, especially in the ever surprising dredging work under the water table. People can see more than sensors can measure and a monitoring system can display, and the human can react to the so common “unexpected”. One of the most important emotions to be rationalised is that many operators fear to be out of control on an enormous machine under their responsibility. It is considered a starting point in the development that the operator being out-of-control will be totally unacceptable. Even the feeling must be prevented under all circumstances, let alone the actual condition. Safety by total control is, under all circumstances, a must. Therefore a transition between automatic and manual control 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 the operator touches the control levers, the automatic operation stops and control over any movement is returned to the operator himself. The take-over function is integrated in such a way, that it assures that the operator's reflexes and his train of thought will not be affected by the automatic control in progress. The operator can move the excavator whenever he wishes, without first having to execute difficult computer actions to intervene: the automatic system does not interfere with operator intentions. At the operator's will the automatic control moves aside gracefully and, when the he steps on the pedal again, the automatic system resumes operation.
(Illustrations: Figures 6 and 7)

Figure 6. Digging a bite pattern automatically.

Figure 7. Machine with movement memory.

In addition to the operator's overriding safe control, several extra safety features were introduced in hardware as well as software. Main target of those safety features is to prevent as much as possible certain technical (hydraulical) failures on the machine can induce unwanted situations. However this was more an increased awareness of those situations on all excavators than because of automation of the excavator. Example is the in dredging dangerous fact excavator rotation in general is not stopping direct when an operator releases his controller; he has to counter the rotational movement. The excavator simulator proved to be a decisive tool in developing an automation accepted by the operators. The foot pedal concept was developed and tested on an excavator simulator and finally assessed to be favourable by three operators of different ages.

Further benefit of the simulators proved to be the ability to train operators in the correct use of the artificial intelligence to learn quick and when is the most beneficial to use the automation in a certain dredging job. For practical purposes all operators received a first training how to use automation on the simulator. The operators provided quite candidly their personal feed-back on the simulator training The general opinion was that they preferred to be trained first on a simulator like this, representing fairly accurate their machine. It is seen to let them build-up knowledge and self-confidence with the applied technology, and test certain limit settings without the risk of damaging an expensive machine, previous to be charged to operate the automated Liebherr 995 machine. In the morning of the first training session, the automation was in general perceived as "complex" and "difficult". In the afternoon that attitude changed with most operators to understanding the system and realization of the potential benefits in future dredging jobs.

In principle the simulator comprises all thinkable information to replace the reality. It can be described as a software combination of the excavator machine split in operator chair, graphics & hydraulics, the monitoring system and the excavator automation part. In the simulated outside environment (Figure 8) also the barge to be loaded is included. Today's computer power, dredging experience and the previous developed ground model from the current generation of hopperdredger and cutterdredger simulators made it all possible to create also a very realistic simulation of excavator dredging. As conclusion can also be stated the excavator simulator increases the acceptance of the excavator automation and a more standardized dredging method with excavators in general.

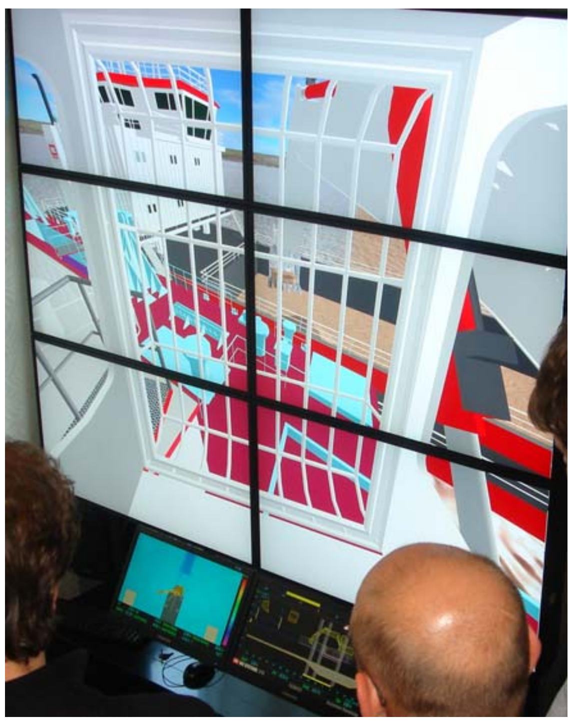

Figure 8. The virtual excavator, software has replaced steel.

The different operators have embraced the system as useful for their dredging job, the final operational experience. The conclusion of observing the actual operation can be that the dredge can be operated automatically in a safe and very accurate manner by only one foot of the operator. (more or less: manual set-points are set earlier) A typical eye opener showed up during a large part of the finishing cleaning up job, which was executed at about the maximum possible effective dredging depth of the LIEBHERR 995, here configured for a depth of about 22 metres (65 feet),. With the automation by foot pedal, no challenging hand operation was necessary any longer on this extreme depth. Of course the job could have been done by hand by the skilled operators. The operators testified that this would not have been possible with the same combination of speed and required accuracy. Manual operation would have translated in this particular case in dredging more over-depth, with, because of this depth, a longer cycle time. The automation saved cost in time and less over-depth dredged.

The finished areas were surveyed after the dredge had been moved. The survey showed the performed job had met the requirements well, and met the targets and stayed within the tolerances permitted. This reflects the typical result of well designed automatic process execution: the security of repeatability.

In addition to the excavation we have at the last, but not least step of the cycle (Figure 9), the step-by-step loading of the barge in an automatic mode. The machine is programmed to dump every load exactly next to the previous discharged bucket. It has shown that a skilled operator can also achieve that goal. However, this task is also recognized as a difficult one and it is not realistic to expect each time an accurate repeat of that part of the process.

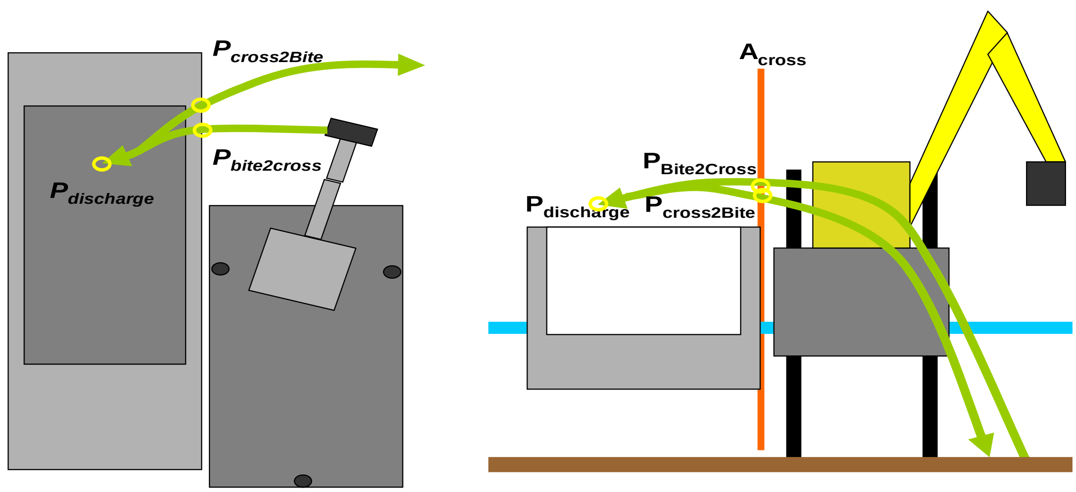

Figure 9. Reference points for the dredging cycle.

The operator can always interfere in the automatic cycle. For instance, if he considers an extra cleanup bite necessary, or when an anomaly (like a large stone) is encountered in the routine cycle.(Figure 10) If manual digging re-starts the normal automatic dredging sequence after that (which will often be the case) the operator can turn on the automatic system again to resume automatic operation. If he judges it not desirable to continue with the 'plan' of the automation, he can "teach the AI" for instance one or more additional bites, till the automation follows his plan.

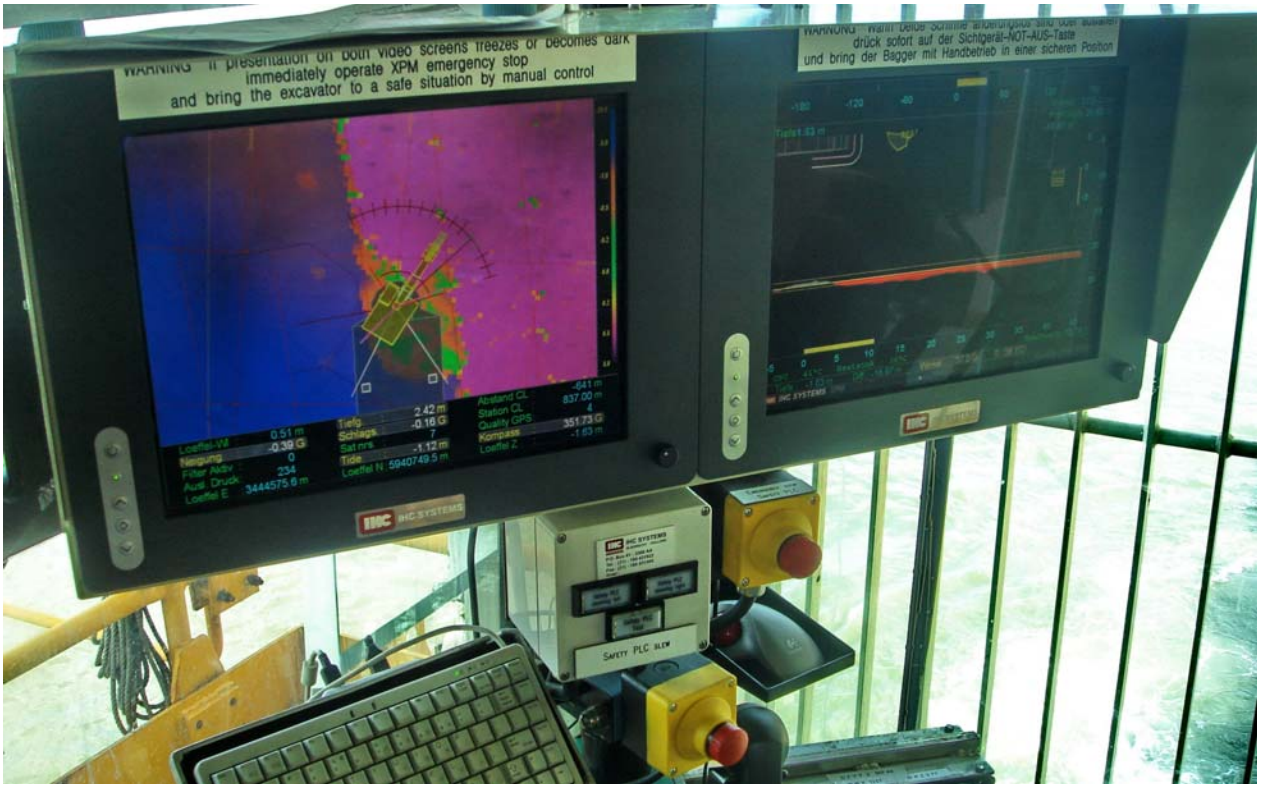

Figure 10. The MP40 pontoon and her nerve centre in the cabin of the Liebherr 995.

CONCLUSION

The conclusion is that automation increases production and accuracy. Also: the operator on an automated dredge excavator can be moved out of the immediate routine control loop. Only partly however, as the operator's task is moving to become a process operator. A comparison that its limited in our industry: the technology does not allow yet operators to leave the cabin and to operate the process remotely a possible future step. However, the automation contributes to a greatly enhanced capacity of the tool, by generating continuous high outputs at high accuracies. The promotion of 'operator' on an automated backhoe to become a "submerged landscape engineer" has some merit.

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