Maintenance Robotics in TBM Tunnelling

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ABSTRACT

Among the various domains of the construction sector, tunnelling exhibits its own specificities in particular in terms of risks. Several techniques have been developed through the years in order to make excavation works more efficient and safer. Tunnel Boring Machines (TBM) were invented some 60 years ago and the concept since went through several significant improvements that have nowadays made them the preferred approach for the vast majority of tunnel projects, whether in hard rock or in soft ground.

In TBMs a rotating cutter head carries excavation tools that are submitted to wear, which can be intense in hard and abrasive grounds. Replacing these excavation tools is a difficult operation especially in pressurised TBMs, in which two main problems appear: operator health and safety due to repeated compression and decompression cycles; slow overall interventions reducing the overall TBM efficiency. In addition, working close to a potentially unstable excavation front is inherently risky; handling devices weighing close to 200 kg is also a source of accidents and skeletomuscular trauma.

Through the EC-funded NeTTUN project we intend to solve the above three problems, by developing a specialised maintenance robot. This system will handle the whole cycle of excavation tools replacement on a TBM. This paper goes through the currently implemented maintenance operations with a focus on pressurised machines, the possible alternatives, and describes the NeTTUN robotic system under development. It explains the general concept and rationale behind the technical choices made, states the targeted performance, and gives some insight on its detailed design.

Keywords -

Tunnel Boring Machine, TBM, Pressurised tunnelling, Robotised maintenance, Risk reduction

1 Introduction – Tunnel Boring Machines

A TBM is basically a mechanised machine to excavate tunnels of circular section. The first designs of such machines may be considered to date from the mid 1850's but modern hard rock TBMs were actually born in 1950 with the design of James S. Robbins first used in a dam diversion project (Oahe Dam in Pierre, South Dakota). James S. Robbins later on invented the disc cutter, which he first used in the Humber River Sewer Tunnel in 1956 in replacement of picks. Disc cutters have since become the industry standard and equip all successful hard rock tunnel boring machines.

Excavating through soft ground and particularly below the water table raises additional issues to that of the hard rock situation, mainly with the need to hold the excavation face and prevent any ground collapse. This led to the invention of pressurised shielded TBMs in which the ground pressure (at the front of the machine) is compensated for inside the TBM. Two main approaches were invented: the Earth Pressure Balance (EPB) and the Slurry TBM.

Invented in Japan in the early 1970's the earth pressure balance method has actually revolutionised soft-ground tunnelling by allowing the construction of shallow tunnels in soft-ground, as is the case in the majority of urban tunnel projects. EPB tunnelling is currently the most commonly used approach in the excavation of metropolitan subway systems, rail and highway tunnels, and other civil works projects that require tunnelling in a soft soil, below the water table.

The underlying principle of the EPB method is that the excavated ground itself is used to provide continuous support to the tunnel face by balancing earth pressure against the forward pressure of the machine. As the cutter head rotates the shield advances by extending its hydraulic jacks. The excavated soil enters the excavation chamber located between the cutter head and the sealed bulkhead, at a rate that is determined by the machine advance speed. The excavated material is removed from the chamber through a screw conveyor, the throughput of which is controlled so as to maintain the pressure inside the chamber equal to that of the ground at the front.

Another major characteristic of an EPB TBM (also common to all shielded TBMs) is that the tunnel lining (supporting the constructed tunnel) is installed simultaneously with the machine advance, in the form of subsequent rings assembled from reinforced precast concrete segments. Several segments (usually around 8) together with a key form each ring that is built inside the rear part of the shield, i.e. in a somewhat protected area. The final result is that a continuous and sealed concrete tube is built ensuring the stability and reliability of the completed tunnel.

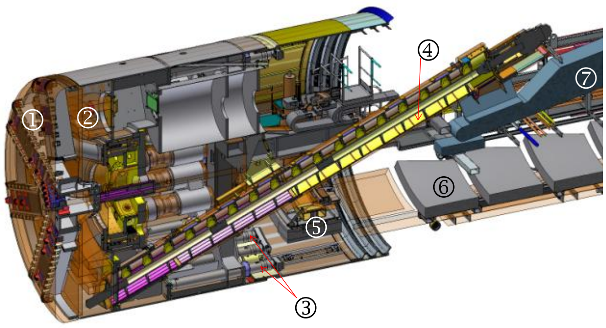

Figure 1. Typical Sketch of an Earth Pressure Balance Machine (EPB) (NFM Technologies)
(1) Cutter head; (2) Excavation chamber; (3) Thrust cylinders; (4) Screw conveyor; (5) Segment erector; (6) Segment conveyor; (7) Belt conveyor

2 TBM Maintenance

2.1 Excavation tools

One of the main activities concerning the maintenance of TBMs is related to the wear of the excavation tools located on the cutter head. Similarly to the drill of a drilling machine, depending on the nature of the material to be excavated (drilled), the tools wear more or less quickly and have to be replaced with new ones. The tools describe concentric circular tracks and are chosen according to the ground/rock characteristics, with two main categories:

- Drag bits for soft ground: these are static scrapers acting as a lathe tool
- Disc cutters for rock: they apply intense pressure locally on the rock face, generating cracks and progressively chip the rock

Figure 2 shows photos with dimensions of a typical disc cutter and of a drag bit.

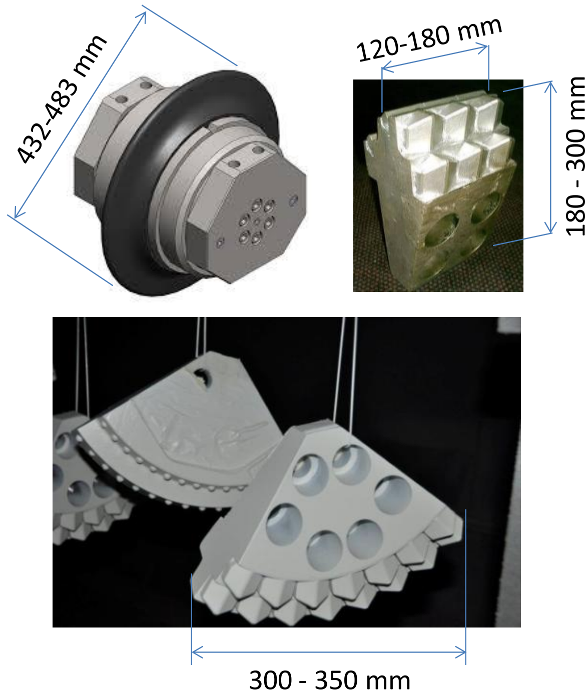

Figure 2. Disc cutter (left), drag bit (right) peripheral scrapers (bottom)

A drag bit weighs 8-25 kg approx (up to 50 kg for the peripheral ones) while a disc cutter is in the range of 130-250 kg.

2.2 Replacement operations

Replacing worn/damaged excavation tools is a difficult task. By their weight only, handling disc cutters can be harmful. Operating in the confined and often muddy excavation chamber at a height of 10-15 m above the “floor”, handling a pneumatic wrench, screws, nuts and washers standing on a small platform adds significant risks. Overall the productivity is low, e.g. replacing 10 disc cutters requires 2 operators for some 6 hours.

However the problems rise dramatically in the case of pressurised TBMs because entering the chamber requires specific actions as described now.

2.2.1 Hyperbaric interventions

This consists in replacing the pressurised soil inside the chamber with compressed air, into which the operator can “dive”. However, because the human body cannot naturally undergo pressure changes, this can only be achieved by following strict procedures that have been developed for subsea divers, based on decompression stops. A vast majority of excavation tools is performed through hyperbaric interventions on pressurised TBMS, which are consequently equipped with a manlock that provides the required compression and decompression cycles. Indeed TBM interventions are actually quite often performed by professional deep-sea divers.

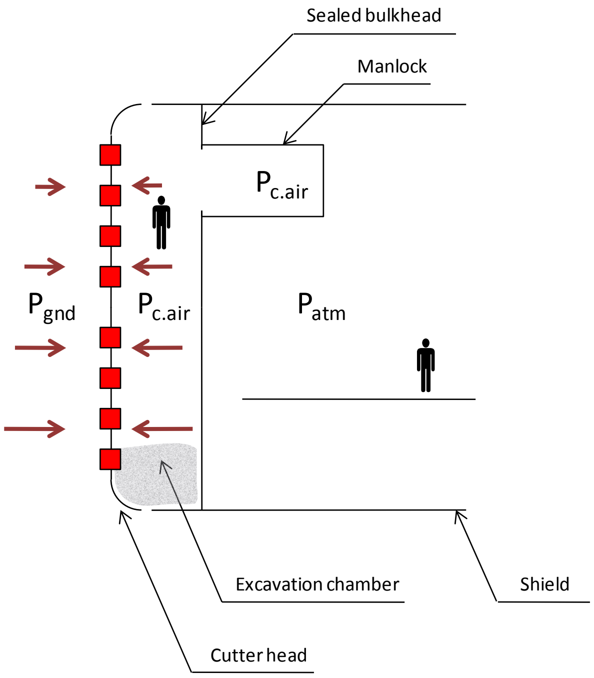

Figure 3. Hyperbaric intervention concept

Figures 4 give decompression times for typical interventions. Increasing the pressure beyond a few bars requires a change of gas: air can be used up to 3 or 3.5 bar (with oxygen decompression), then Nitrox up to 4 bars then Trimix (saturation diving).

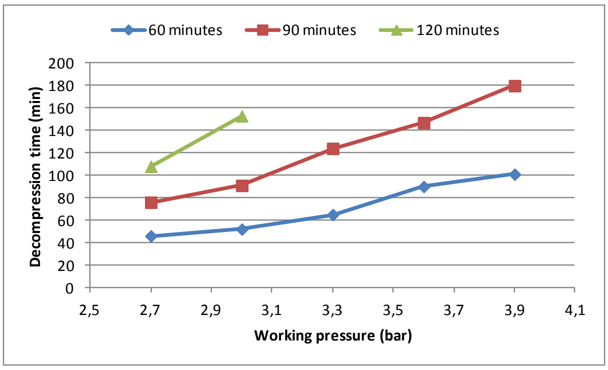

Figure 4. Decompression time vs. working pressure, for various intervention times in compressed air

It should be noted that the standard practice is to prohibit excavation while operators are occupying the manlock. This allows for an immediate intervention in case of an emergency situation in the chamber or cutter head. With the above graphs, this demonstrates how decompression issues can rapidly become problematic.

The main issues raised by hyperbaric interventions are health impacts and loss of TBM productivity.

- Health and Safery

The UK Health & Safety Executive has analysed the consequences of working in intermediate pressure compressed air. The retrospective study of decompression illness (DCI) in the UK indicated that at certain pressures its incidence was around 2% of all exposures. More worryingly it showed that over 20% approx. of the exposures commonly undertaken by shift workers in tunnelling (those over 1 bar pressure for 4 hours or more) resulted in DCI. It was concluded that on some contracts up to 50% of shift production workers experienced DCI at some time during the contract, a situation which was considered to be wholly unacceptable (Lamont, 2006).

At higher pressures i.e. over 3.5 bar (ITA Report No 10, 2012) specific equipment and special gas mixes and/or saturation techniques are recommended (Lamont, 2012). Such procedures are expensive and time consuming although the duration of work in the pressurised area can be very limited for health and safety reasons. The level of risk is always high, due to the exposed working conditions close to the potentially unstable excavation front however we have no reliable data on accidents occurring during hyperbaric interventions and to the repeated compression-decompression cycles (Le Péchon, 2003).

- Productivity and associated costs

According to feedback from our TBM end-user partners in the NeTTUN project, the overall cost of a 1 hour maintenance stop of the excavation is in the range of 2,500 to 10,000 Euros but can reach much higher levels through delay-related penalty schemes. It should be noted that 1 hour of effective maintenance time results in a 2-hour stop because of the idle time related to the decompression (in the case of a single manlock, which is the case on machines smaller than 12 metres). This clearly shows the substantial added value that our robot provides to the TBM excavation industry by cutting this idle time to half (see section 5).

2.2.2 Atmospheric pressure exchange

In many cases, hyperbaric interventions cannot be avoided. However, some TBM manufacturers such as Hitachi (Fernandez et al., 2011), Kawasaki or Herrenknecht designed cutter heads accessible from the inside to allow the operators to work at atmospheric pressure.

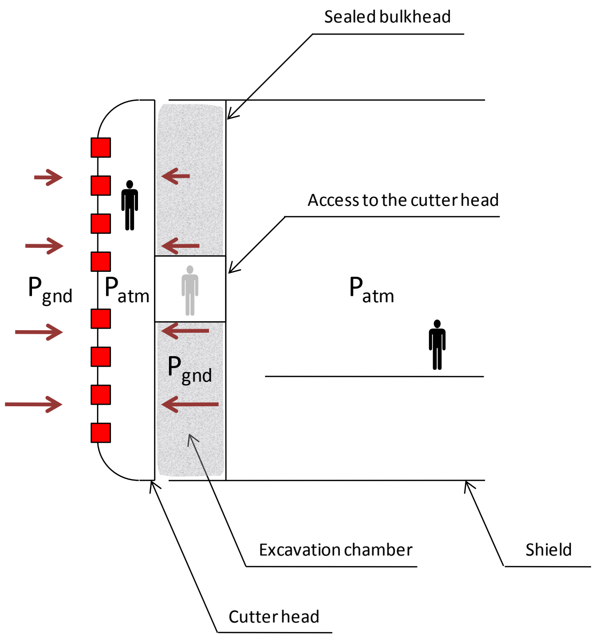

Figure 6. Atmospheric Pressure intervention concept

In this approach each excavation tool is installed in an individual lock, operated as shown in figure 7.

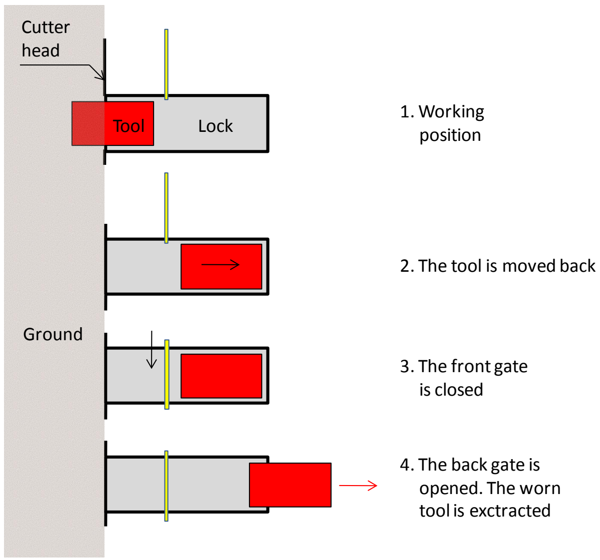

Figure 7. Atmospheric Pressure tool exchange

This solution has a number of drawbacks: it increases the weight and the size of the cutter head, limits its opening ratio, impacts the positioning and spacing between disc cutters. Working inside the cutter head, even if larger than usual, does not eliminate risks but presents a range of different risks: accidents and musculoskeletal trauma because of the very restricted working space and confined environment; catastrophic consequences in case of a mechanical failure.

The increased weight of the cutter head increases the stress on the main bearing and penalises the manoeuvrability of the TBM. Such large cutter heads are also more prone to clogging. The reliability and the added cost of this complex solution seldom meet the end user requirements in terms of efficiency and cost effectiveness.

3 The NeTTUN Robot Approach

3.1 Goal

The primary goal is that of improved safety, i.e. dramatically reduce the number of human interventions in the cutter head. The target is to perform 80% of the interventions with the robot, thereby reducing the number of related worker accidents by a factor of 5. A secondary goal is to improve the overall TBM efficiency by avoiding idle time related to personnel decompression and reduce the unitary intervention time e.g. for a disc cutter replacement cycle.

3.2 Requirements and Challenges

3.2.1 Dimensions and TBM applicable diameter range

One of the biggest challenges to overcome is the very limited space available for the robotic system. Analysing the available space, both for the storage room and the deployed robot itself, we have fixed the dimensional constraints to 1.5 x 2 x 3 m (stored position). In its various operating positions the arm has to extend over 2 m and handle a 300 kg load at full extension, and also move inside a 1-1.3 m long excavation chamber. None of the off-the-shelf industrial robots comply with these three requirements: implementing an industrial robot would lead to a limited operational range or a limitation in minimum TBM diameter or size. It was also observed that only 5 degrees of freedom were needed whereas industrial robots usually offer 6, useless complexity. On the basis of these statements we decided to design a specific system.

3.2.2 Productivity

In current hyperbaric interventions, the replacement of one disc cutter takes approximately one hour and jobsite data analysis has shown that maintenance operations can represent 15% to 25% of the activity time of the TBM (Maidl et al., 2008). Simplifying and shortening this task decreases the risks on operators and increases the productivity of the machine. The robotic solution under development aims at doing the maintenance either automatically or by remotely operated means. It is based on a specific arm equipped with a purpose-built manipulator that can move inside the excavation chamber of the TBM.

3.2.3 Ergonomics

The current cutting tools are designed to be changed by human operators; two pairs of hands are generally required to mount and lock a disc cutter on the cutter head, and its locking mechanism can consist of more than 10 separate elements (bolts, nuts, wedges…). The tools and their locking mechanism therefore need to be rethought in order to allow for an easy and reliable robotic manipulation. Both the disc cutter and drag bits (including the gage scrapers) have been redesigned based on a self adjusting mechanism with a high level of mechanical integrity.

3.2.4 Design of the manipulators

Because of the very different shapes, dimensions, position on the cutter head, and mounting scheme of disc cutters vs. that of drag bits, we designed two dedicated manipulators. The height and the width of the manipulator are limited by the structure of the cutter head and especially the side walls of the cutter head arms. The manipulator needs to incorporate all the functional components for cleaning, visual assessment, locking, and unlocking the cutting tools while being compact enough to reach the required positions.

Both manipulators share a unique interface and can be interchanged manually by disconnecting/connecting a set of cables and hydraulic pipes.

3.2.5 Assessment of wear

One of the operations currently performed by the operators in hyperbaric interventions is to inspect the excavation tools and assess their wear. This is done visually, also using wear gages. Several TBM manufacturers or end-users have recently designed disc cutter wear measurement systems. NFM Technologies have also designed such a system in which the wear is measured electronically and that delivers other information pertaining to the status of each monitored disc cutter. The system communicates with the TBM control computer and provides the robot with the necessary information feedback for an autonomous operation.

4 NeTTUN Robot System Description

4.1 General information

The robotised maintenance system presented here is designed for TBMs with a diameter above 8.5 metres. The system works for both types of pressurised TBMs (EPB and Slurry). It can be implemented on a Hard Rock TBM assuming a redesign of its cutter head. It can withstand an absolute air pressure of up to 10 bars, a temperature between 10°C and 50°C, and a humidity ratio of up to 100%. All actuators are hydraulic using extremely rugged devices that have been specifically designed for the project. The exclusive use of hydraulic actuators for the robot is justified by the higher robustness and reliability of this technology and the better compactness and higher power to weight ratio that we can achieve with hydraulics compared to electric technology. All these attributes are essential for our application.

The same system can be used on TBMs from 8.5 to 16 m without any mechanical change; this would only require changing the software parameters and the description file (coordinates of all disc cutters and drag bits on the cutter head).

The system handles both drag bits and disc cutters, the latter in the current 17" and 19" standards but is dimensioned to face a further increase in size - and consequently weight - that is progressively taking place.

4.2 Hardware architecture

The robotic system is made of five main components: the storage enclosure, the cutting tools logistics system, the deployer, the articulated arm, and the manipulator. Only the last three components are described here.

The deployer deploys and positions the articulated arm in the excavation chamber. The articulated arm positions the manipulator on the cutting tool that needs to be changed. The deployer has three Cartesian degrees of freedom: forward/backward, up/down and left/right. The articulated arm provides additional degrees of freedom to manoeuvre through the front door, unfold into the excavation chamber, and align the manipulator in the appropriate orientation. Two degrees of freedom are required for the articulated arm: one rotation to compensate for the unavoidable inaccuracy in positioning the cutter head; one rotation to reach the peripheral tools. The most challenging dimensioning constraint is the required torque for the second rotator joint (pitch): given the weight of a disc cutter and of the manipulator itself, this device should deliver more than 12 000 N.m. Each type of cutting tool requires a specific manipulator: one for the disc cutters and another one for the drag bits. The manipulator's main task consists of holding the tool and unlocking/locking it. It is also used for cleaning by its pressurised water jets.

The control unit for the robotic arm will be placed in the storage enclosure, whereas the electronics for the articulated joint and the manipulator will be directly integrated in these components. A global interface combining the robotic arm, the manipulator and joint, the door of the storage enclosure, and the positioning of the cutter head will allow the operators to remotely conduct the maintenance tasks from the TBM control room.

4.3 Operational area

The robot will be stored in the upper part of the TBM, in a storage enclosure connected to the shield. A rear door gives access to the personnel and allows the supply/removal of cutting tools. The robot is deployed into the excavation chamber through an automatic front door and then operates along the upper vertical radius of the cutter head. Special attention has been given to the design of the doors (opening direction, locking system, sealing) to guarantee their safety with respect to the operational pressure inside the storage enclosure. By appropriately positioning the cutter head, the robot can cover all the cutting tools situated in the external part of the cutter head radius (50 to 60% of the radius, depending on TBM diameter) (see Fig. 8). The central tools that cannot be reached by the robot are subject to much less wear due to the relatively short distances they travel during excavation; they typically represent around 15 % of the total maintenance operations on the cutter head. They are not covered by the robotic operation because of the little advantage it would bring compared to the added complexity it would involve. Figure 8 below shows the operational area of the system.

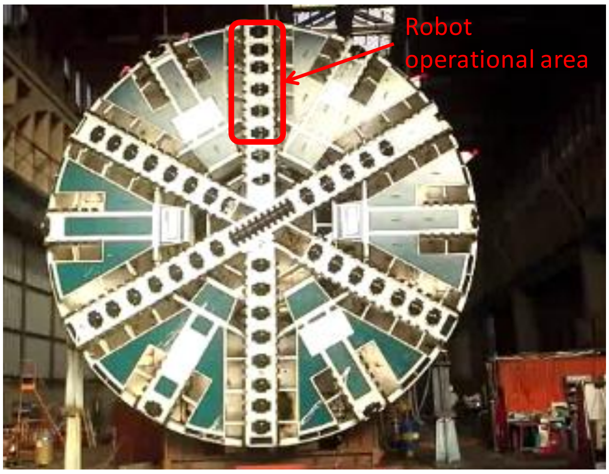

Figure 8. Operational area of the robotic system (10 m EPB for the Riyad metro, with 59 disc cutters and 305 drag bits in total)

4.4 Software architecture

4.4.1 Concept

The control architecture of the whole robotic system is divided in 4 main components that are connected together as shown in figure 9: the deployer and arm control unit, the manipulator control unit, the tool buffer control unit and the high-level control unit.

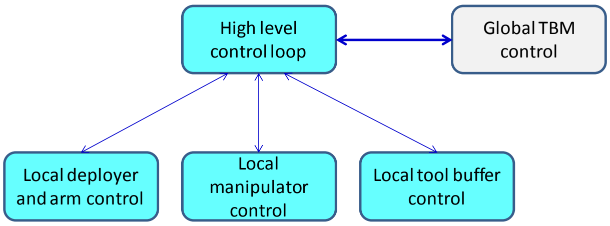

Figure 9. Software architecture

4.4.2 Deployer and arm control unit

This control unit is dedicated to the position control of the arm. It collects the sensor information from the robot and controls each actuator in position. It is connected to the high-level control unit from which it receives real-time trajectory instructions. It sends back the state of the actuators and sensors.

4.4.3 Manipulator control unit

This control unit handles the gripping of the tool and the unlocking/locking operation. It gathers the sensor information and through PID controllers, controls in position the linear actuators and the motors. It is connected to the high-level control unit per CAN bus. It receives commands from the high-level control and sends back the state of the motors and sensors.

4.4.4 High-level control unit

The high-level control unit is a Linux PC managing the whole scenario and trajectory supervision. It controls the subsystems (deployer, arm, manipulator, and worn/new excavation tools handling system) in real-time and provides a graphical interface to the user. It will also be connected to the TBM PLC to be able to initiate the maintenance sequence (positioning of the cutter head in rotation, opening of the storage room front door) and handles operational safety issues. Additional sensors such as cameras will also be directly connected to this unit.

5 Robotised Maintenance Operation

The operational sequence of the robotised maintenance operation is shown in figure 10.

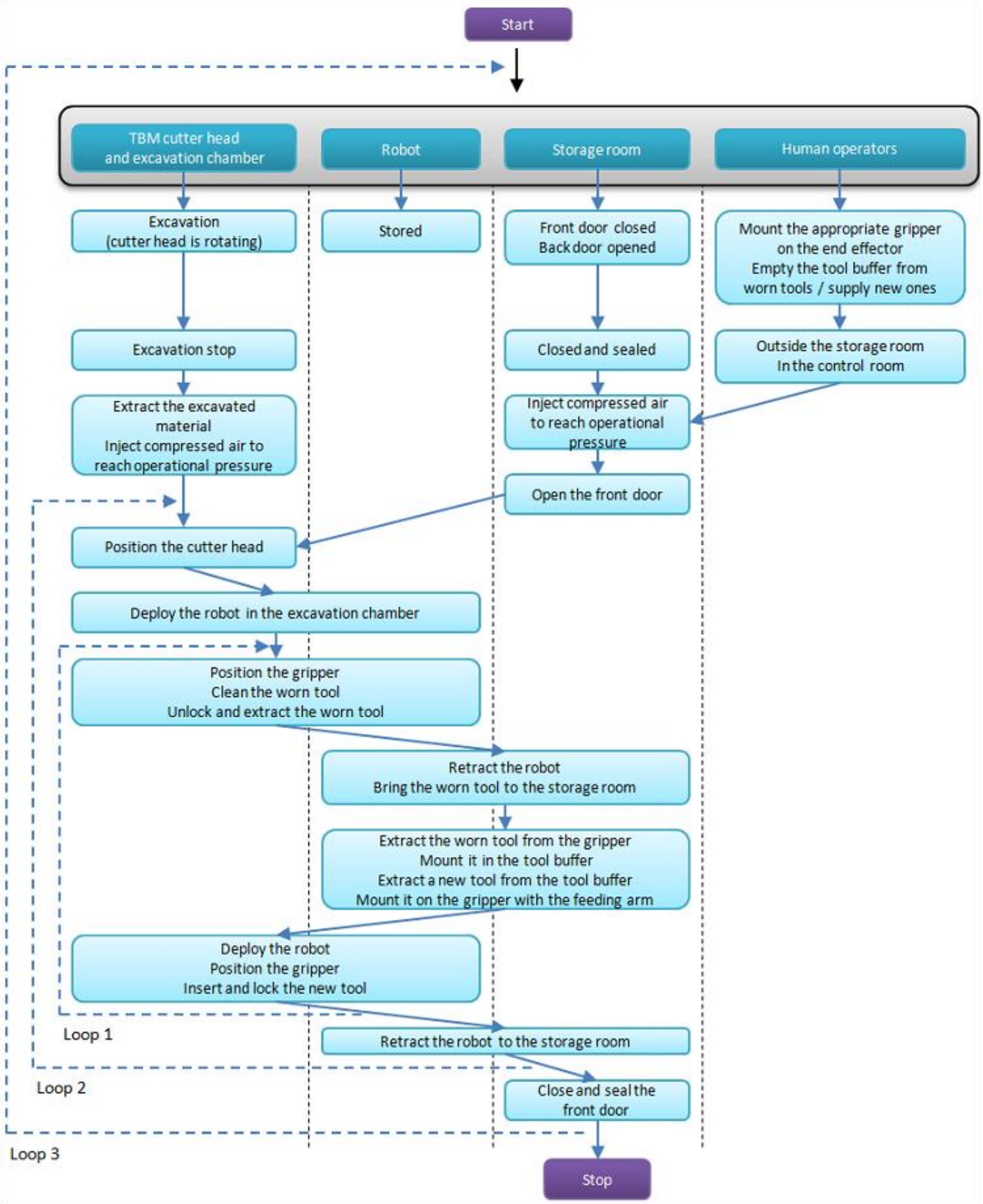

Figure 10. Robotised maintenance sequence

Loop 1 represents a cutting tool replacement cycle on a cutter head radius where other cutting tools need to be replaced as well. Loop 2 shows a replacement cycle for the case where only one cutting tool is worn on the corresponding cutter head radius. A complete replacement cycle for all the worn tools on the cutter head is presented in loop 3.

The average cycle time for the replacement of one tool in loop 1 is 15 minutes; less than half the average time it takes to carry out the same task in the current manual hyperbaric mode.

All cleaning, maintenance, and repair operations for the robotic system will be carried out manually in the storage enclosure by the operators working at atmospheric pressure during TBM excavation.

6 Conclusion and Outlook

In this paper, we have presented a concept for a robotic system dedicated to the maintenance of TBM cutter heads. Our main target through robotised maintenance is to eliminate the risks to humans from routine cutter head maintenance operations in pressurised environments. When implemented, this system will facilitate the maintenance of TBMs working at pressures above those currently permitted by law in many countries and will also greatly improve the productivity of the TBM by reducing its idle time, especially through the elimination of the decompression procedures that the operators go through in the current manual hyperbaric interventions.

The detailed design of the system is in progress, new cutting tool prototypes have been designed, approved, constructed, and now being soon field tested. The detailed design of the robotic device including the manipulators is being finalised and construction of a prototype robot will start in the coming months. A full scale mock-up system has been designed and will be constructed to accommodate the robot for the first operational tests at NFM by end 2015. The mock-up and the prototype will then be transferred to DFKI for the development of the control algorithms, the implementation of the manipulators, and the final tests prior to the system integration in a TBM.

In future developments of this project, one final goal and two intermediate challenges will be addressed: The first challenge is to develop and implement a haptic feedback system for the end user interface to offer a more informative and realistic environment for the remote operator. The second challenge is to develop an automatic system for the exchange of manipulators in the storage enclosure (disc cutters or drag bits).

Depending on our end-users demands, our final goal could be to adapt the NeTTUN robotised maintenance system to carry out the cutting tool replacement operations immersed in liquid bentonite in the excavation chamber, i.e. dispense with the need to use compressed air to fill the empty volume.

Acknowledgements

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