Conceptualising an Inspection Robot for Tunnel Drainage Pipes

G Ecker¹, B G Zagar¹, C Schwab², F Saliger³, T Schachinger³ and M Stur²

¹ Institute for Measurement Technology, Johannes Kepler University Linz, 4040 Linz, Austria
² ASFINAG Service GmbH Süd, 8074 Graz, Austria
³ ÖBB-Infrastruktur AG, 1020 Vienna, Austria
⁴ Sachverständigen Büro für Boden + Wasser GmbH, 4210 Gallneukirchen, Austria

gabriel.ecker@jku.at

Abstract. For inspection purposes first ideas of an in-pipe robot are presented. The idea of a rover with respect to the environmental conditions, as well as details of structure, actuation, measurement and control concepts is discussed in this document. It should be able to navigate through rather narrow and buckled drainage pipes with diameters not much larger than the robot itself, so the design is aiming for a most compact and potentially self-disassembling solution necessary for cases of stuck robots.

1. Introduction
The problem of scaling, consisting of mostly calcite [1], [2] in drainage systems, of both road and railway tunnels, has been noticed in water pressure-relieved tunnels all around the world [1], [3], [4] reducing the in-pipe water flow and clogging the drainages. Clogged drainage pipes can cause breakdown of tunnel operation due to water ingress [4] or can even endanger the tunnel structures [4], [5]. To avoid such situations, the tunnel drainage system needs to be maintained regularly. At the moment, drainage cleaning represents the largest part of all regular maintenance work that is necessary and is causing high costs [5], [6].

Under the current predetermined maintenance regime, tunnel drainages are cleaned at fixed intervals mostly, which either depends on experience or is determined by opportunities of track availability, budget, etc. [6]. So the idea of determining the location and thickness, as well as the removal resistance of calcite and other sediments, independent of the tunnel traffic and using this information to improve the cleaning process is obvious. Beside flushing nozzle-based cameras, there are preliminary studies of measurements using stationary sensor systems of various kinds [6], integrated into newly built drainage pipes, with moveable inspection devises or by estimating the in-pipe conditions out of the surveyed data, like drainage water or scaling properties as well as geologic facts and experience [7].

Such information is currently raised in a uniform inventory of the conditions of Austria’s railway tunnel drainage system, as part of the Task Force Drainage (TFD), allowing estimations on the cleaning intervals and location [7]. Another objective of the TFD is to minimize the in most cases necessary closures of the affected tunnel when inspection and maintenance work is done [7]. A kind of robot, including sensor systems, able to drive through the drainage pipe system, may allow a
measurement based inspection, providing additional information of the in-pipe conditions, without effecting the tunnel operation.

There are already existing robots for oil and gas pipelines [8], but their physical dimensions differ significantly from those required in drainage systems. Conventionally, these are steered manually, enabled through cameras [9]. The evaluation of the recorded video material is then done by inspection. Therefore, an autonomous robot is desirable, particularly considering the total length of tunnel drainage pipes that might easily be in the order of hundreds of kilometres [6].

In summary, the objective of this project is to develop a robot for inspection purposes only, capable of navigating independently through narrow drainage pipes, passing kinks, junctions and half-open tubes. Thereby also recording the position and measuring the thickness of sediments spatially resolved.

2. Locomotion strategy

2.1. Environmental conditions

The study is for typical drainage pipes with 250 mm outer diameter with a maximum reduction of 20 mm by scale deposits. Kinks up to 30° and man holes with half-open tubes must be navigable. Additionally, junctions to maintenance pipes for cleaning are encountered regularly and must be resolvable. The robot should be robust against the conditions in the pipes (dust, air humidity, alkaline water, various water levels and currents) and should need little maintenance [6].

The technical properties of the pipes may not be negatively changed by the, even many times, passing rover and the inspection must not impair the operation of the tunnel, anyway [6].

As a result of the long distances, in the order of the tunnel lengths, to be covered in the drainage system the robot cannot be powered tethered via cables.

Locomotion should be possible in both directions, so that in case of blocked pipes the rover can move out in reverse. If the robot gets stuck or totally fails, pressurised water must be able to destruct it into manageable pieces to be washed out easily. Cleaning operations by the robot were explicitly not defined as a goal in the project, since there is currently no possibility of removing the loose scale deposits after flushing by an autonomously operating robot.

2.2. In-pipe locomotion

As consequence of possibly half-open pipe sections, pipeline inspection gauge (PIG) (Figure 1A), screw (Figure 1D) and inchworm robots (Figure 1F) are unsuitable. Furthermore propeller driven rovers (Figure 1G) cannot be used, since no minimum water-level can be guaranteed. Walking concepts (Figure 1H) are generally complex, quite large and slower than other types [10], leaving wheeled, tracked and snake robots as suitable locomotion strategies.

Because of the advantage when generating the necessary friction of tracked locomotion [10], [11] and reduced effort to control compared to snake type [11], a robot concept with four tracks allowing wall-pressing for increased friction [11] is chosen. Furthermore, a rover with quadruple support is able to also pass the aforementioned half-open pipe sections without the risk of toppling over.

2.3. Adjusting mechanism

Passing kinks, junctions and half-open tubes is definitely challenging. To overcome these problems, a kind of deformable robot is advantageous. Based on the mechanics from [12], an adjusting mechanism, described in section 5.1., is designed. The combination of linear actuation and spring loaded tracks allows adapting the robot to the pipe's inner diameter and enables to generate additional friction if deemed necessary. This degree of freedom may permit driving from half-open tubes into closed ones by reducing the rover’s size and adapt it again in the closed pipe section.

2.4. Passing elbows

Tracked type robots with wall-pressing technique require a differential drive to allow them to corner, this can be done with individual steerable motors or gear mechanisms [8].
When the rover needs to pass an elbow its outer diameter has to decrease, springs and adjusting mechanism are allowing such changes. Figure 2 shows the worst-case scenario in an 30° elbow. With the geometric relations

\[
d = \frac{D}{\cos(15°)},
\]

\[
x = \frac{L}{2} \tan(15°),
\]

\[
b = d - x = \frac{D}{\cos(15°)} - \frac{L}{2} \tan(15°),
\]

the minimal size of the robot can be calculated from the track's length and pipe's inner diameter. This leads to a maximum outside dimension \( b \) of about 206 mm, calculated with a pipe diameter \( D \) of 230 mm and a track length \( L \) of 240 mm.

3. Basic features

Figure 3 gives an overview of the basic construction of the robot. Its main parts are four track units (components A), connected through four spring assemblies for each track unit (components C) with the skeletal structure, including linear bearing and stepper motor (component B).

The overall length of the robot is 414 mm, the track length is 240 mm and its square outline can vary between 173 mm and 330 mm. It is able to pass 30° elbows as described in section 2.4. According to the calculation of the used CAD software the rover weighs slightly over 5 kg.

4. Track unit

Figure 4 shows the components of one track unit. A: Brushless DC motor with mounted sprocket-wheel, B: Battery pack, C: Waterproof case, D: Passive sprocket-wheel, E: Ball bearings, F: Track. They are all mounted via two stainless steel supports, one on each side.
4.1. Actuation

An efficient actuation system, including rotary encoders as well as the energy storage must be devised. Narrow pipe diameters require space-saving designs wherever possible, therefore and also because of the humid environment a classic brushed motor with a then necessary gearbox is not the most appropriate choice. With a brushless DC outrunner motor direct actuation and easier corrosion protection are possible.

As a consequence, as main actuator the brushless DC motor DF45L024048-A2 [13] is used. It is an outrunner motor with a rated power of 65 W that includes three hall sensors [13] to facilitate its control. Tests showed that these hall sensors are absolutely necessary when driving such motors at low speeds and noticeable torque without field oriented control.

Due to space constrains the sprocket-wheel is glued onto the rotor and its star like extension meshes into the track, preventing the motor from slipping through. The motor contains iron as ferromagnetic material that easily corrodes when subjected to water. Therefore, all parts of the motor are covered with epoxy resin and the bearings are replaced with non-corroding ones, this allows a wet operation, i.e. water is allowed to penetrate into the motor.

Another advantage of a brushless DC motor compared to a brushed one is the possibility of freewheeling in cases of failure or when the motor is switched off. In return, a more complex motor controller is required and the cost is higher.

The battery pack contains four 18350 lithium ion cells, resulting in a 14.8 V, 1100 mAh accumulator. A battery management system (BMS) is limiting the maximum current drain to 7 A.

To save energy while in motion one or two tracks can be turned into passive mode, depending on how much feed force is needed and in which orientation or pipe section the rover is operating in. Anyway, the battery's state of charge must be monitored to avoid unplanned standstills in the tubes.

To determine the robot’s position, the distance covered is measured by counting turns of the tracks, when at least one of them is set to passive mode the accuracy is even higher, since the belt cannot slide through accidentally.

4.2. Electronics

As a consequence of the limited space in the pipe a compact controller is required. Furthermore, movable cable connections are to be avoided in order to not hamper waterproofness. Therefore, it is obvious to choose surface mounted devices (SMD) for the brushless controller. To avoid movable cables and to avoid plugging when track units are changed Wi-Fi connected microcontrollers seems to be a good choice.

Verification of the prototype track unit (see section 4.4.) showed that a DRV8306 brushless controller in combination with three CSD88584Q56DC half bridge drivers, all from Texas Instruments® provides sufficient drive power even at low rotation speeds.

An ESP8266 microcontroller with integrated Wi-Fi is used to implement an overlain regulator circuit. The microcontroller also ensures the communication with the main controller and feeds back measured data, like the number of turns, the state of charge of the batteries and errors.

The electronic circuit is designed to limit the motor current to 6 A resulting in a maximum peak motor power of approx. 90 W. So overall the rated drive power is 260 W (4 x 65 W), with peaks up to 360 W (4 x 90 W). The estimated mean drive power depends strongly on the applied normal force, determining the friction force, as well as the water current situation and is expected to not exceed 30 W in the mean, resulting in a minimum operating time of approx. 2 hours.

4.3. Mechanics and materials

The humid and alkaline environment conditions, typically encountered in drainages and the demand for weight minimization require certain materials to be chosen. In this context plastics for low mechanical loads and stainless steel for higher loaded components are suitable. Therefore, the cases as well as the sprocket-wheels are made from plastic and the bearings, ball pins, screws and nuts are made from stainless steel.
The spring assemblies connected through ball joints press the track units against the drainage wall which in combination with the silicone rubber material of the tracks gives sufficient friction even on wet pipe walls. To get the whole case containing all electronics and the battery pack waterproof an O-ring is used and the feed through for cables is sealed with epoxy resin.

4.4. Prototype
Figure 5 shows a photo of one track unit, still with external electronics, used for the verification of the actuation system. It also contains the battery pack powering the whole system. The spring assemblies are also mounted, but not yet attached to the skeletal structure. This prototype is able to read in the desired rotational speed via Wi-Fi and controls the motor speed with a PI-regulator. While testing the unit it turned out that the reachable torque at desired drive speeds as well as the forward forces when pressing the track against a wall are more than sufficient for the assigned task, while the motor current stays well below the maximum of 6 A. Therefore, this particular controller is used further on.

5. Skeletal structure
Figure 6 shows the components of the skeletal structure. A: Front case, containing stepper motor and electronics, B: Back case, containing battery pack and the rotary encoder, C: Linear bearing, D: Lead screw, E: Stops, sliding bearing, F: Connecting sheets.

5.1. Mechanics and motion
To drive the adjusting mechanics a corrosion-resistant and power-saving linear actuation, which is able to withstand considerable axial forces, allows self-disassembling in case of failure and holds the track units in position, is needed. A lead screw made from stainless steel, actuated by a stepper motor seems suitable. Due to the low angle \( \alpha \) (Figure 6) there are considerable axial forces to be expected. Therefore, an additional bearing, accepting axial loads, needs to be installed. To prevent it from blocking there are slide bearings placed inside the stops. Moreover the stops, including the back case, avoid contact of two tracks. Both cases as well as the stops are made from plastic to save weight and to allow for Wi-Fi connections. The waterproofing is again done with O-rings. For the lead screw shaft seals are used.

5.2. Electronics
As counterpart to the Wi-Fi connection, the data storage, the control of the stepper motor and for numerical processing as well as measuring purposes another microcontroller is used. This main controller again is an ESP8266 microprocessor, controlling the stepper motor via a MP6500 stepper driver from Pololu®. A rotary encoder allows determining the distance between the connecting sheets. On the one hand, this is necessary for the calculations, on the other hand, this allows getting feedback of the translational position, so that the motor current can be adapted and end positions can be set. All electronics in the skeletal structure are powered by a two cell lithium ion battery pack located in the back case (Figure 6 component B). The BMS limits the current to 2 A. The lead screw was designed to be self-locking, so no holding torque is required.

![Figure 5](image1.jpg) **Figure 5.** Track unit prototype with electronics separated.

![Figure 6](image2.jpg) **Figure 6.** Components of the skeletal structure
6. Spring assembly

The main components of a spring assembly are shown in Figure 7, namely: A: Base body, B: Sliding axle, C: Ball socket, D: Spring stopper, E: Measuring coil, F: Spring.

6.1. Mechanics and Materials

The main task of the spring assembly is to press the track units against the pipe walls resulting in sufficient friction for the drive to move even in adverse conditions. Furthermore, its positional information can be used to determine the thickness of possible sediments. The base body as well as the spring stopper is made from plastic, so the alternating magnetic field caused by the coil can pass through. Between these two parts a spring is inserted and the travelling distance of the mechanism is 20 mm.

Ball socket, spring stopper and the sliding axle are mounted together, resulting in a movable part, gliding in and lead by the basal body. The latter is flexibly connected to the skeletal structure, ball socket and ball pins of the track units are assembled representing a ball joint.

6.2. Measuring principle

The task is to find a suitable measuring principle that allows determining the length of a spring assembly and thus the radial extension of the tracks. Due to potential corrosion problems, unprotected electrical contacts need to be avoided.

Inductive principles like eddy current sensors seem to be most suitable, because they work in a contactless manner and can be fully encapsulated. According to [14] the equivalent inductance $L$ of an eddy current sensor can be estimated to be

$$L = L_1 - \frac{4 \pi^2 f^2 M^2 L_2}{R_2^2 + \left(2 \pi f L_2 \right)^2}, \quad (4)$$

where $L_1$ is the self-inductance of the sensor, $R_2$ and $L_2$ are the equivalent resistance and self-inductance, respectively, of the axle and $M$ is the mutual inductance between the sensor coil and the axle [14]. The displacement and the actual length of a spring assembly can be determined from the measured inductance via its characteristic. A copper core is inserted in a centre bore of the axle, so $R_2$ decreases, resulting in a higher change in inductance when the axle is displaced.

Assuming the situation shown in Figure 8 with opposite track units (components A and B) staying parallel to the skeletal structure. From the mean lengths of the involved spring units (a, b, c, d) as well as the measured distance between the connecting sheets x and the given dimensions l, q and D the complete outer dimension $H$ can be calculated as

$$H = \frac{\sqrt{2} (x-l)^2 (a^2+b^2)-(x-l)^2-(a^2-b^2)^2} {2 (x-l)} + \sqrt{2} (x-l)^2 (d^2+c^2)-(x-l)^2-(d^2-c^2)^2} + q + D. \quad (5)$$

Figure 7. Components of a spring assembly.

Figure 8. Robot in an arbitrary situation.
This is done for each opposite pair of track units, resulting in two values proportional to the thickness of the sediments. To eliminate the impact of pipe deformations a reference measurement in recently cleaned drainages can be done. As a consequence of the 90° angularly displaced tracks used as measure points calcite sediments in between cannot be detected.

7. Conclusion
In this contribution a concept for an in-pipe inspection robot has been presented. The self adapting design includes solutions for passing challenging drainage pipe sections like kinks, junctions and half-open tubes. Additionally, the rather narrow pipe dimensions requested compact systems combining various features. Its behaviour in cases of failure is planned, resulting in a potentially self-disassembling and freewheeling solution. The design also demonstrates measurement strategies for determining the location as well as the thickness of sediments. The materialization and the verification of the presented principles are ongoing.

8. References
[1] Wegmüller M C 2001 Einflüsse des Bergwassers auf Tiefbau/Tunnelbau Stäubli AG Zürich ISBN: 3 7266 0052 3
[2] Stur M, Ottner F, Schachinger T and Wriessnig K 2013 Calcium hydroxide (Ca(OH)2) as a component of scaled deposits in tunnel drainage systems Proceedings of the 11th International Probabilistic Workshop, pp. 419–438,
[3] Stur M 2011 Problems of scaling in tunnel drainage systems Master thesis University of Natural Resources and Life Sciences Vienna
[4] Chen Y, Cui Y, Barrett A G, Chille F and Lassalle F 2019 Investigation of calcite precipitation in the drainage system of railway tunnels Tunnelling and Underground Space Technology vol 84 (Elsevier) pp. 45-55
[5] Jung H, Han Y, Chung S, Chun B and Lee Y 2013 Evaluation of advanced drainage treatment for old tunnel drainage system in Korea Tunnelling and Underground Space Technology vol 38 (Elsevier) pp. 476-486
[6] Schachinger T, Saliger F, Zagar B, Stur M and Schwab C 2018 Current research by ÖBB Infrastruktur AG on scale monitoring without track closures Geomechanics and Tunnelling vol 11 (Wiley) pp. 277-285
[7] Schachinger T, Sperger L, Heissenberger R and Wagner O K 2017 Task Force Drainage (TFD) - The project for life after Geomechanics and Tunnelling vol 10 (Wiley) pp. 779-787
[8] Brown L, Carrasco J, Watson S and Lennox B 2019 Elbow Detection in Pipes for Autonomous Navigation of Inspection Robots Journal of Intelligent & Robotic Systems vol 95 (Springer) pp. 527-541
[9] Nassiraei A A F, Kawamura Y, Ahraya A, Mikuriya Y and Ishii K 2007 Concept and Design of A Fully Autonomous Sewer Pipe Inspection Mobile Robot “KANTARO” Proceedings 2007 IEEE International Conference on Robotics and Automation (IEEE) pp. 136-143
[10] Mills G H, Jackson A E and Richardson R C 2017 Advances in the Inspection of Unpiggable Pipelines Robotics 2017 (MDPI) pp. 3-8
[11] Shao L, Wang Y and Chen B G X 2015 A Review over State of the Art of In-Pipe Robot 2015 IEEE International Conference on Mechatronics and Automation (IEEE) pp. 2180-2185
[12] Moghadam M M, Arbabtafi M and Hadi A R 2011 In-pipe inspection crawler adaptable to the pipe interior diameter International Journal of Robotics and Automation vol 26 (ACTA Press) pp. 136-145
[13] Nanotec 2015 Brushless DC Motor DF45L024048-A2 Datasheet
[14] Tian G Y, Zhao Z X and Baines R W 1998 The research of inhomogeneity in eddy current sensors Sensors and Actuators vol 69 (Elsevier) pp. 148-151

Acknowledgment
The authors would like to acknowledge the partial funding of the research presented in this article by the Austrian Research Promotion Agency (FFG) as part of the project 860566 (Drainage-Eye).