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Design and Implementation of a Control System for a Tunneling Robot

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Abstract—The development of a tunneling robot for trenchless drilling has many different design aspects. Suitable hardware requires to be developed that can withstand the torques and forces that are generated by the drilling of the tunnel. A suitable route requires to be plotted that considers the maneuverability of the robot and avoids any obstacles or existing infrastructure. The control of such a system requires to be implemented in such a way that the system can follow the desired route while maintaining the required drill speed and avoid becoming stuck within the tunnel created.

Keywords—Tunneling, Trenchless, Drilling, Control, Robotics, Modelling

I. INTRODUCTION

There are several different services (water, communication, power) running beneath our cities. With increasing demands for these services and the replacement of outdated service conduits there is a need to upgrade and lay new services. Normally to achieve this, large areas of land need to be excavated to allow the services to be laid. Trenchless drilling is a method that is used to avoid the excavation of large areas. The RoBot for Autonomous unDerGround trenchless opERations, mapping and navigation (BADGER) [1] project is developing an autonomous robot that can carry out trenchless drilling. To achieve this the motion of the system is modelled on a worm. The control system requires to replicate this motion while maintaining a constant drill speed.

This paper presents the initial control system design for BADGER and for the Kinematic Investigation Technology (KIT) system that is being used as a testbed for the BADGER control system.

The paper presents KIT in Section II with the current 1D kinematic model of KIT provided in Section III. The hardware control for KIT is presented in Section IV with the migration to the electrical actuated BADGER module presented in Section V. The paper is concluded in Section VI.

II. KINEMATIC INVESTIGATION TECHNOLOGY

BADGER is currently a system that is 4m long with a cutting head diameter of 0.25m with an overcut of 0.05m. The full BADGER system is being constructed in one location with custom parts being supplied from across Europe.

The overall system is difficult to transport and is currently undergoing system testing. For these reasons a method of developing and testing the control system for BADGER without access is required. To achieve this, the Kinematic Investigation Technology (KIT) was developed. KIT is a scaled model (1:2.5) of BADGER and replicates the movement system of BADGER.

The movement of BADGER is achieved using three components: the clamp, the propulsion system, and the steering system. Each of these systems is identified in Fig. 1 and Fig. 2.

Fig. 1. Clamp system

Fig. 2. Propulsion and Steering system shown with drill head

The clamp, Fig. 1, is a pneumatic clamp that expands to clamp against the side of the tunnel. The clamp, when expanded, allows an element of BADGER to move without the whole unit moving. This pneumatic clamp has been demonstrated to work in granular material and is suitable for holding a segment of BADGER in place despite the forces and torques travelling through the BADGER system.

The propulsion system, Fig. 2, consists of three hydraulic actuators that allow a segment of BADGER to travel 0.1m. This motion occurs while the attached clamp is expanded. The propulsion system can be driven with either velocity or position controllers with feedback provided by a linear transducer. This combination of propulsion and clamps replicates the method used by a worm to propel itself by a series of internal contractions and expansions that result in a net displacement [2].

The aim for BADGER is to steer along the y (pitch) and z (yaw) axis. The steering system, Fig 2, consists of three independently controlled hydraulic actuators situated 120° apart on the diameter of BADGER. Each actuator can vary its length and is connected to one side with a ball joint and is clamped to the other side. The combination of length variations of these three actuators provide BADGER with angular motion in both the pitch (y) and yaw (z) axis. That is left or right or up or down when viewed from the drill head of BADGER.

Forward motion is achieved as shown in Fig. 3. The drill head is represented by the triangle. The next two segments are active. Each houses a clamp, a propulsion system and a steering system. The final segment is a service module designed to house a mechanism to coat the walls of the tunnel as BADGER moves forward. This final segment also houses a propulsion and steering system. When C is shown, then the clamp at that segment is active (i.e. inflated), when inactive (i.e. deflated) C is omitted. Overall, BADGER is actuated by three propulsion and three steering systems, with the two clamps being activated or not as needed (Fig. 3).

Three motions can be achieved with this configuration.

- Discrete motion

Each element of the system moves one after the other and the drill head is not continuously moving forward

- Continuous Motion

The drill head is continuously moving forward with every element of the motion overlapping another element to ensure the continuous forward motion of the drill head. To achieve continuous motion, the clamp system needs to operate instantaneously. Currently the pneumatic clamp system is responding in the range of seconds.

- Quasi – Continuous Motion

This motion considers the current clamp system response time is truer to the actually achievable motion. Parts of the motion overlap with each other (Fig. 3) and this overall continuous motion is a function of the clamp inflation/deflation time.

The target motion would be continuous motion as this would allow for continuous drilling with no pauses. However, to achieve this the clamping system would need to operate instantaneously which cannot be achieved.

The Quasi – Continuous motion, which allows for clamping time, is achievable as the system combines motion and clamping at the same time and can provide near continuous drilling.

Fig. 3. Diagram representing BADGER motion

The forward motion of BADGER is simple and involves a repeating pattern as shown in Fig. 3. At Step 1 the system is assumed to be at rest. Step 2 the drill head begins to move forward cutting into the substrate. When the drill head is nearing the maximum throw of the actuators, the clamp begins to deflate (Step 3), allowing the next propulsion segment to begin to move forward. Nearing the second segment's maximum throw (Step 4) the system's second clamp begins to deflate while the first inflates (Step 5). The second segment moves towards the first segment (Step 6) while the drill head is also moving forward. Nearing the maximum throw of the drill head, the second clamp inflates while the first deflates and the final segment is brought forward (Step 7). Step 8 shows the first segment against the drill head with the final segment against the second segment. At this point the system is in the same configuration as that of Step 4. The motion of the system continues using the method described and Fig. 3 shows the progression of the drill head throughout the motion cycle.

III. MODEL OF KIT

KIT is a scaled version (1:2.5) of BADGER and thus is designed to have similar systems and to achieve the same type of motion. Fig. 4 shows the configuration of one KIT segment that includes the steering, propulsion (extending section) and clamp systems.

Fig. 4. KIT segment

The linear motion of KIT was first modelled kinematically and forward motion was demonstrated. A simple controller that extended each segment to full extension then activated the next (as in Fig. 3) was used to show that a simple kinematic controller could be used to demonstrate the motion of KIT, and by extension BADGER.

Fig. 5 provides the results of a forward movement of KIT in accordance with Fig. 3. First, it shows the start and final position of the system during this test. Each circle represents a point on KIT's body. Then, it shows the forward motion of the system's tip (equivalent to the drill tip). The forward motion is near continuous with only slight pauses in the motion. Finally, the extension and contraction of each actuator is shown: each actuator extends to the maximum and then fully contracts, with the next then repeating the movement pattern.

The propulsion system is designed to have a throw of 0.1m (with a 0.05m variant available for additional testing) and the clamp section can be seen at the end. At this time, a pneumatic clamp system at this scale (roughly 12cm diameter) was found to be problematic. The clamp system used on KIT is designed

around a servo that extends pads that push into the pipe that KIT is tested in, see Fig. 8 for the experimental setup. This system has been demonstrated to work well and is suitable for testing the control algorithms being developed.

Fig. 5. Data from a simulation of the forward motion of KIT

The steering system has the same capabilities as that used for BADGER and can achieve the designed range of $\pm 5^\circ$ in pitch and yaw. Larger angles can be achieved by turning in

intervals of 5° as needed. A kinematic representation of the steering mechanism was created, where given the desired orientation (y, z), the required actuator lengths are calculated. The kinematic calculation was carried out and the full system was simplified to allow the control of the steering segment. The equations generated are relevant for both KIT and BADGER with only the parameters representing the position of the actuator end points with respect to each other and the centre of the plate, requiring to be updated. Fig. 6 is the KIT steering system being tested.

Fig. 6. KIT steering system test

IV. CONTROL OF KIT

As described, KIT is used as a test bed for BADGER control algorithms. Two low level algorithms are required. One that replicates the forward motion and a second that replicates the steering motion.

Each part of the system was tested individually to ensure that the system responded as expected. The linear motion was simple as this only involved the use of a single linear actuator that contained an inbuilt position controller.

The on-board position controller for each linear actuator was used to ensure that the requested extension length was reached. For the initial tests on KIT this was determined to be the full extension of the actuator. This is shown in Fig. 7. This data shows the motion of KIT along a pipe. The experimental setup can be seen in Fig. 8. KIT has been demonstrated to move along the pipe in a controlled fashion using the algorithm set out in Section II.

Fig. 7. Feedback data from two propulsion segments on KIT

Fig. 8. Photograph of a KIT segment being test in a pipe

With linear motion demonstrated steering is also required. Fig. 9 shows an output from the KIT steering segment against a desired output. The output was measured by a tilt sensor. The data shows that the steering system can move to the desired angle when requested. To achieve this, individual PID controllers and linear transducers are required. Using, as input, the desired angles, the length of each actuator is calculated. Each actuator is driven in a controlled way and the angle is achieved. Note that the system relies on the feedback from the individual linear transducers as there is no tilt sensor on the actual steering mechanism to provide feedback.

Fig. 9. Photograph of a KIT segment being test in a pipe

V. MIGRATION TO BADGER

The motion of BADGER replicates that of KIT. There is a high-level component and a low-level component.

The high-level component is designed to have the desired path (the calculated drill path) as input and from this the position and orientation of the BADGER drive segments are calculated. At this time, Inverse Simulation [3, 4, 5, 6] is being investigated as the high-level control algorithm. Inverse Simulation is out with the scope of this paper and the reader is directed to [3, 4, 5] for further information. The Inverse Simulation will generate a list of actuator positions for both the propulsion and steering mechanisms based on the desired output path. These actuator positions will be passed to BADGER where a series of PIDs will be used to realise the desired actuator positions.

The kinematic forward motion has been established in simulation (Fig. 5) and on-board KIT (Fig. 7, 8). For BADGER the forward motion is the same and the results show the same plots as that of Fig. 5, allowing for increased segment and actuator length. The steering platform simulation results from this can be seen in Fig. 10. The code running the steering algorithm is the same as that of the KIT simulation and hardware, with only the parameters associated with the increase in diameter and actuator lengths changed.

Fig. 10. Simulation of BADGERs steering system

The next stage is to demonstrate this on a BADGER segment. BADGER will run the PIDs on a PLC supplied by TT Control [7]. This PLC can run a PID for each of the actuators. At this stage, the actuators are being tested on the BADGER electrical propulsion and steering unit. This unit is shown in Fig. 11. The unit functionally represents the BADGER hydraulic unit and is a suitable replacement for testing on the scale of BADGER.

Fig. 11. BADGER Electrical propulsion and steering unit

The unit consists of six electrical actuators, three for the propulsion and three for the steering. The propulsion section has a single linear transducer to provide feedback on the motion of the propulsion part. Each of the steering actuators has an individual linear transducer to provide feedback. It should be noted that the propulsion unit actuators are mechanically coupled with no individual motion. Whereas the steering actuators are attached to ball joints that allow free movement of each actuator.

Each actuator has an associated PID that is used to drive the actuator based on the feedback provided by the transducer and the position requested by the user.

For the propulsion segment, tests were undertaken and the segment was shown to work as expected. Given a desired position the propulsion system was able to move there. The repeatability of the system is shown in Fig. 12.

With the mathematics of the steering section derived, the PIDs were set up to control each of the actuators individual. Tests were carried out using a tilt sensor to provide user feedback. Fig. 13 shows the desired pitch with Fig. 14 showing the desired yaw and Fig. 15 showing the position of each of the steering actuators. It can be seen from this repeated test that the system can be controlled.

Fig. 12. BADGER Electrical propulsion and steering unit

Fig. 13. Desired pitch angle

Fig. 14. Desired yaw angle

Fig. 15. Position of the actuators

VI. CONCLUSION

This paper has presented an overview of BADGER, a robotic system for trenchless drilling. The method of achieving the desired motion of BADGER is examined and the development of an experimental testbed (Kinematic Investigation Technology – KIT) for conducting laboratory experiments using a small scale analogue system is described.

The current results from both KIT and BADGER have been presented. The desired motion of BADGER can be achieved using the gait sequence supplied. The results have demonstrated that the individual segments of BADGER can be controlled. This shows that with the correct actuator inputs to the low-level control system the BADGER segments can move as desired. With a suitable high-level controller implemented the complete BADGER gait sequence can be achieved.

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