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BADGER

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Deliverable

D3.2. Nonlinear Mathematical Models and Simulations

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List of definitions & abbreviations

Abbreviation	Definition
DOF	Degree of Freedom
FDIR	Failure Detection Isolation and Recovery
KIT	Kinematic Investigation Technology
ROS	Robotic Operating System
SILO	Singularlogic

Executive Summary

This report provides an initial description of the required nonlinear mathematical model of the robot, the requirement for the model, the simulation environment that it runs within, and progress made to date. A roadmap for the continued development of the model is provided. The model is an iterative development that should follow the development of the system.

The nonlinear mathematical model is a mathematical description, with suitable parameters, of the BADGER. It includes kinematics and dynamics models of the robot but also the models of the actuators and influence of the environment over the the robot. The idea is that the model can be used to test concepts and controllers without having access to BADGER, or risking damage to BADGER.

The model will be used as a testbed to support the development of the control and navigation algorithms for BADGER. With an accurate representation of BADGER, the tests undertaken in simulation should be representative of tests on BADGER. This means that development of motion controllers can be undertaken with no access to BADGER. The motion controllers will be developed in conjunction with the model. This means that BADGER hardware development can happen in parallel with motion controller development. In addition, the proposed controller and FDIR algorithm (Inverse Simulation) requires an accurate representation of the device to be controlled to ensure correct operation.

The model presented in this document is an early iteration of the final model and only contains translational motion along the drilling axes. The motion achieved is by the repeated extension and retraction of the linear actuators. A simple description of the linear actuators is used in this early iteration. This has been done for two reasons. The initial device to be modelled is KIT, a smaller version of BADGER. KIT uses electro-mechanical linear actuators whereas BADGER uses Hydraulic actuators. The model presented accepts the input from an actuator, allowing different actuators to be tested. Using the repeated motion of the linear actuators it has been shown that BADGER can move forward with the desired controlled motion.

As started, the model is an early iteration as many of the decisions that must be made in order to inform the model have only recently been agreed, and many are still to be demonstrated. In addition, the data required to validate, an important step in the development process, the model has still to be gathered. This was noted at the BADGER kick off meeting and it was agreed that the model would run in parallel with the development of the hardware. A useful mathematical model needs to describe the real system and should be validated against the real system. While development of the BADGER systems are ongoing, the model will be updated to reflect the system.

To aid in the development of the model, the UoG, with the support from the consortium, has undertook the development of a smaller version of the BADGER called KIT. KIT will be used to validate the initial models of the system and provide a means of validating and testing new concepts for the control and design of BADGER.

With respect to a ROS model, which is one of the outcomes of the model, not enough work has been undertaken by the UoG to allow a suitably informative model to be created. However, SILO have undertaken work to form a basic model in ROS that captures the shape and main movements of BADGER.

The critical output from this document is the timeline and development cycle for the model. This is set out and shows that the development of the model will occur in a suitable timeline.

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1. Introduction

The purpose of this deliverable is to provide an update on the status of the mathematical model of BADGER. The basic model of the BADGER and the steps that will be followed in order to develop the model as the BADGER design progresses.

An overview of the BADGER design is provided, as is a simple structure of the model developed to date. The means of further developing the model is also discussed, as are the steps that are being undertaken to support the model development.

1.1 Scope of the Deliverable

This deliverable provides an update on the status of the development of the mathematical model of BADGER. Within this document there is a description of the current model with a demonstration of the output from the model. The most important output of this deliverable is the timeline for the further development of the model and the expected release dates of the model.

1.2 Relation to other Deliverables

With respect to the other deliverables this document forms part of WP3 and is closely related to:

- D3.1 Robot path and motion planning algorithms

  The model developed can be used to develop these algorthims with a representation of a real system.

- D3.3 Guidance system and motion control system design

  The model will provide the initial design environment of the control system design and be used to provide the first estimates for the efficiency of the design.

- D3.4 FDIR System design

  The FDIR algorithms to be used, from the context of motion, will use the model generated.

1.3 Deliverable Structure

Section 2 provides an overview of BADGER and the systems that make up BADGER. Section 3 provides an overview of the model development with Section 4 describing the simulation framework. Section 5 discusses KIT and Section 6 highlights the ROS model. Section 7 provides detail on the continued development of mathematical model for BADGER and Section 8 Concludes the document.

2. BADGER Overview

This section provides an overview of BADGER. The constituent parts of BADGER are presented and the key points required for the model are identified below.

BADGER is to be made up of four modules, each of which has a designated purpose. Each module contributes to the movement of the overall BADGER device. Figure 1 provides a block diagram layout of BADGER with a top-level description of the function of each module presented next.

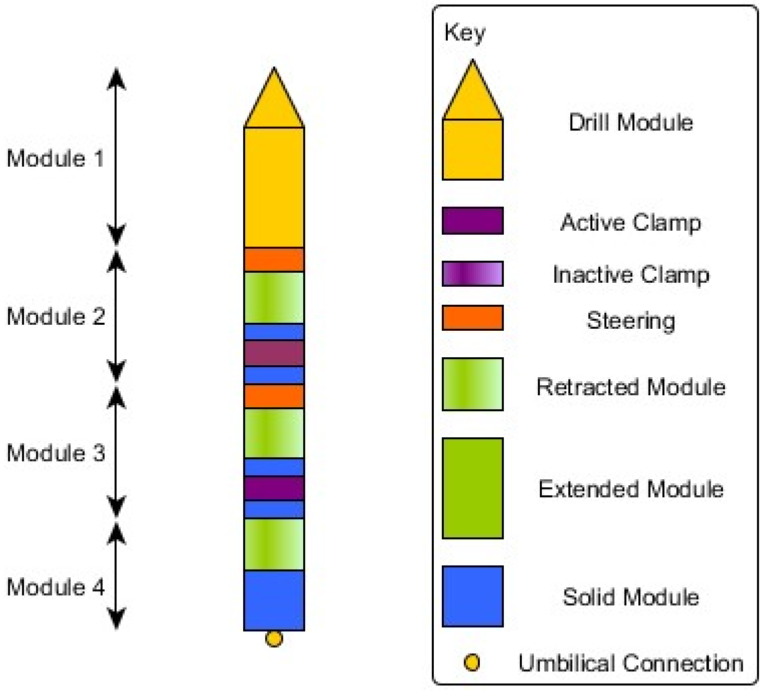


Figure 1: Schematic Diagram of the BADGER

Module 1 The drill module houses the scraper plate for drilling into substrate and the mechanism for rotating the scraper plate. This module also houses the end of the vacuum nozzle, which is used to remove the spoil. The GPR modules that provide obstacle detection and mapping support are also contained within this module.

Joint 1 The first joint is made up from two different systems: A system to provide translational motion, and a second to provide pitch and yaw. The translational motion is provided by three hydraulic actuators. The range of motion is at least 100 mm. The pitch and yaw module is based on a three actuator system which restricts the yaw and pitch to 10° motion.

Module 2 The first module contains the electronics for controlling the systems housed in the Drill module and a ground clamp to enable the translational motion.

Joint 2 The second joint is also made up from two different systems. A system to provide translational motion and a second to provide pitch and yaw.

Module 3 The second module contains a clamp to support the translational motion of the system and additional control and localisation modules.

Joint 3 The third joint contains a translational motion system and a passive yaw and pitch joint.

Module 4 This module contains the mechanism for coating the walls of the drilled tunnel and a downhole FDIR system. This module also contains a passive joint for the umbilical cord to BADGER.

3. Model Development

This section discusses the development of the model. The stages of the model are presented and discussed.

Figure 2 provides the elements of the model required to provide a full model.

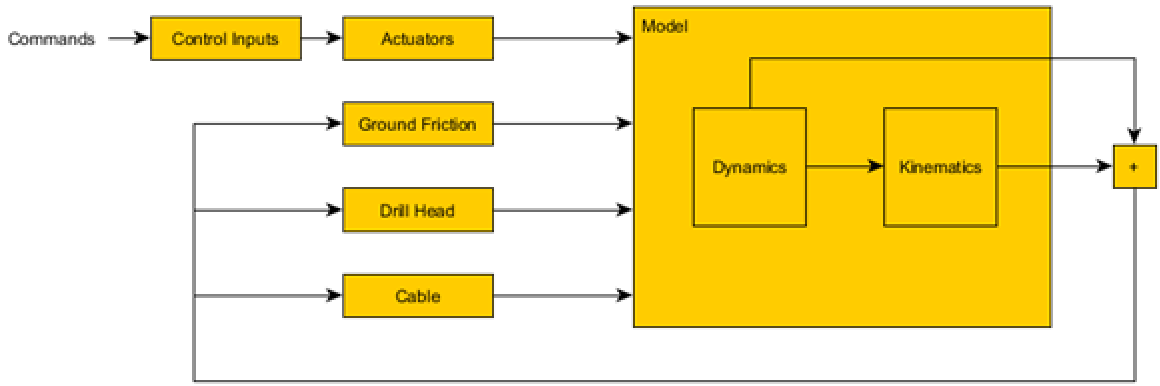


Figure 2: Block diagram of the model of BADGER

Control inputs to model will command the operation of the actuators. The control interface is yet to be established but it is expected that position/orientation and velocities of the drill head, including the actuators distances and velocities, will be the main control variable. The output of the actuation will be the force that is applied to the module, as the model developed will use the Newton-Euler formulation for rigid bodies (dynamics and kinematics). The velocity of the actuation will be internally controlled. However, the velocity of the module is a function of the resistive and actuation forces. Currently very simple models of the actuators are being used as these are waiting formal specification. Once selected the actuators will be tested and the models validated.

The next feature of the system that requires modelling is the Environmental Model. At this stage, only ground friction has been identified as an environmental aspect that requires modelling. Ground friction is to be modelled as viscous friction [2]. Viscous friction assumes that the friction force is proportional to the velocity of the modules. The authors have used this model before [3] and it has proved successful.

As the project evolves, it is envisioned that a two-stage friction model will be implemented. Coulomb friction [2] (which is based on the mass of the module) will be used when the module is static, but this will be replaced with the viscous friction method once the module is in motion.

To establish a friction model, a co-efficient of friction is required. According to the authors experience this number is best estimated through experimentation. Estimates can be made as a starting point but as BADGER and the experimental setups develop then, better estimates of the co-efficient can be made. The methodology used to establish a suitable co-efficient or range of co-efficient will broadly follow that outlined in [3].

Three more elements will require to be modelled because of the envisioned impact on the modules. These are the umbilical Cable Dynamics, the Drill head Dynamics, and the Clamp Mechanism.

The Umbilical cable will be being towed behind the BADGER. The current design is that this cable is attached to the final module. This will affect the BADGER's motion due to the additional mass that needs to be moved. This should mainly affect the last module of the BADGER but it will affect the motion of the other modules as well.

The Drill head will provide a torque that is applied to the complete BADGER system. In the first instance, the model of the drill head will be based on a propeller. The main characteristics of both are the same, as both a torque and thrust will be developed. As the development of the system continues, an improved model will be developed and validated.

The clamp mechanism will need to be modelled, as this could provide a timing restriction on any guidance and propulsion regime. In addition, the dynamics of the system will be altered by the clamps operation. At this time, the clamp mechanism selection is ongoing. For this reason the clamp is modelled discretely; it is either on or off, and it is assumed operational with no failures. As the design matures, the model will be updated to reflect the BADGER design.

3.1 Axis Orientation

Overall Body Fixed Point

The first axis to define is the main body fixed point. This has been selected to be the front point of BADGER as this is a point that will be tracked. A second major axis point to define is the middle of the back of the last module, where the umbilical will be attached. It is assumed that the x-axis is the direction of travel. The forward motion of BADGER (the drilling direction) is defined to be positive along the x-axis. This is shown in Figure 3.

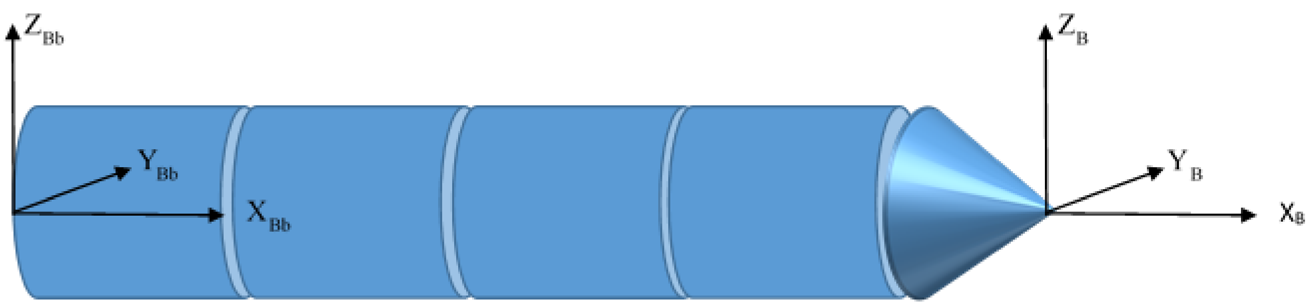


Figure 3: Overall Body Fixed axis

With X_B, Y_B and Z_B representing the x,y,z-axis of the tip of the drill head and X_{Bb}, Y_{Bb} and Z_{Bb} representing the x,y,z-axis of the Back of the Body (umbilical connection).

Module

For each module, two axes are defined: The Centre of Mass (CM) (currently assumed to be the Centre of Gravity (COG) as well), and the tip of the actuation system. A simplified representation is given in Figure 4 below. Forward motion (drilling direction) is positive along the x-axis.

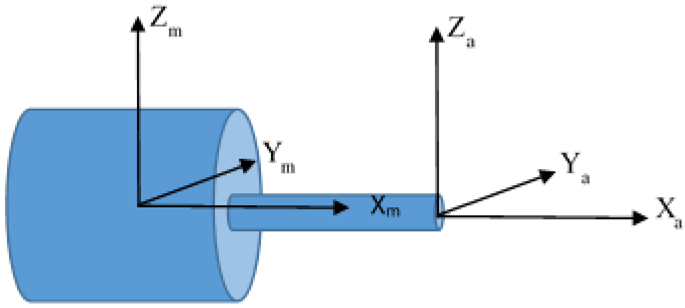


Figure 4: Simplified Module Axis

With X_a, Y_a and Z_a representing the x,y,z-axis of the point at the centre of the tip of the actuator and X_m, Y_m and Z_m representing the x,y,z-axis of the CM of the module.

3.2 Actuator Model

The current actuator model is a simple model that sets a constant speed of travel for the actuator and is either on or off. Once the actuator is fully extended or retracted then the motion stops. The current parameters for the actuator used can be found in Table 1.

Table 1 - Parameters of Modelled Actuator (initial estimates)

Parameter	**Value**
Extension Distance of Actuator	0.1m
Co-Efficient of Internal Friction within Actuator	75
Force Co-Efficient of Actuator	10
Incremental Step Size of Actuator	0.01m

The co-efficients selected have been calculated to ensure the constant speed and force that can be achieved by the actuators is in line with the published speed and force. It should be noted that these numbers are estimated values and may not be achievable. Experimentation with the actuators will be carried out to update these numbers.

The step size is far larger than can be achieved as the idea do this intial model it to provide an indication that the basic motion concept can be achieved.

Currently the actuator model is 1-D operating along the axis of motion. The model consists of the following parameters:

- Run
  Input parameter that indicates the actuator to run or not.

- Direction
  Input parameter that indicates the direction of travel for the linear actuator

- Force
  Output parameter providing the Force being generated by the actuator

- Current distance
  Output parameter indicating the current position of the actuator.

Figure 5 shows the actuator movement. The movement show the actuator extending to the full length and then retracting. There is a pause as the next module operates.

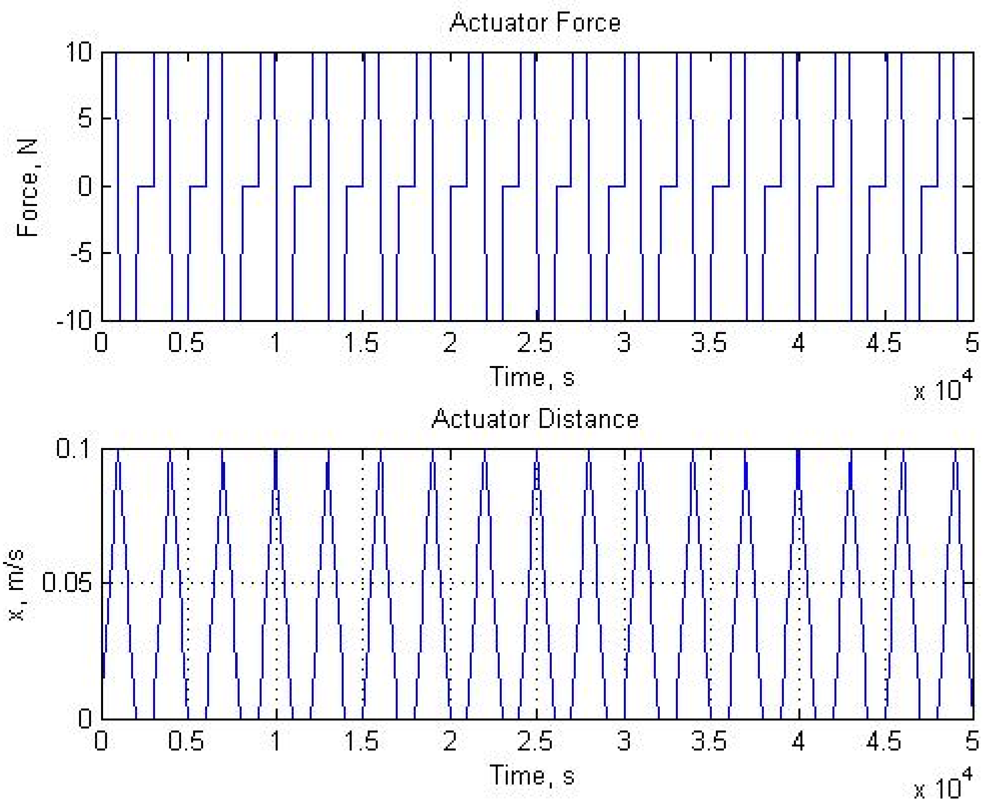


Figure 5: Simplified Actuator Force and Displacement

3.3 Module Model

From the actuator the next item to be modelled is the module. As with the actuator, the module model is an initial simplified model.

The module is modelled as a rigid body and has the parameters stated in Table 2.

Table 2 – Parameters of Simplified Module Model (initial estimates)	
Parameter	**Value**
Mass	10Kg
Co-Efficient of Friction	75
Mass with no input force (Clamp on)	100000kg

The mass and the co-efficient have been selected to provide an overall forward velocity of 0.13ms^{-1}. This has been selected based on the desired speed of the system. These parameters will change as more experimental data is gathered. The clamp mass is used as a means of ensuring that the module does not move.

The module is modelled as a rigid body with the following inputs and outputs:

- Actuator Input Force as applied to CoG and connection point (Input)
- Directional Torque as applied to CoG and connection point (Input)
- Module Actuator Force and Torque at tip of actuator (Output)
- Module Linear and Rotational Velocities at CoG and at tip of actuator (Output)
- Module Translational and Rotational Position at CoG and at tip of actuator (Output)

For the first module, the Drill Torque will need to be considered, as will, the forces and torques applied to the last module because of the umbilical cord. As the project progresses these elements of the model will be added.

3.4 Initial Dynamic Model

The Initial Dynamic Model of Badger considers the four modules to be point masses (M_1, M_2, M_3, M_4). These masses are coupled together by the three similar actuator systems, which are represented by damper (C_A) and spring (K_A) terms. This representation is illustrated in Figure 6 below:

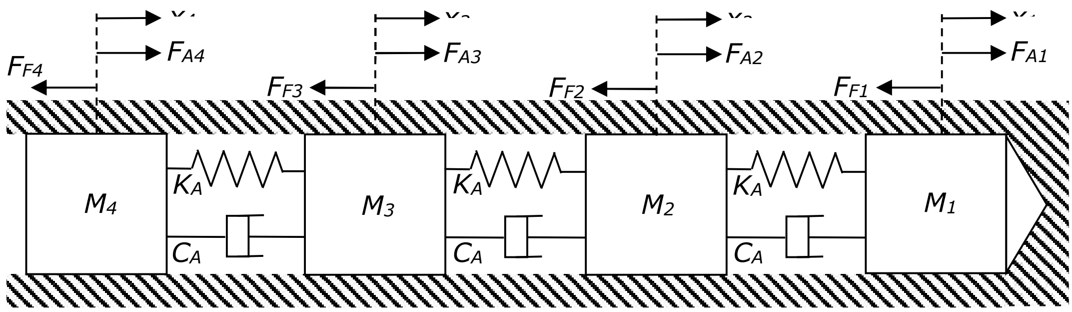


Figure 6: Mass-Spring-Damper Representation of Badger

The displacements of the four masses (x_1, x_2, x_3, x_4) are determined by the application of the actuator forces on the four module masses ($F_{A1}, F_{A2}, F_{A3}, F_{A4}$). In opposition to these motions are the friction forces between the modules and the soil being drilled through (i.e. $F_{F1}, F_{F2}, F_{F3}, F_{F4}$). The following dynamic equations can be derived by considering the combination of the forces acting on each module:

$$\frac{d^2x_1}{dt^2} = \frac{k_1}{M_1}\left[-C_A\left(\frac{dx_1}{dt} - k_2\frac{dx_2}{dt}\right) - K_A\left(x_1 - k_2x_2\right) - F_{F1} + F_{A1}\right]$$
$$\frac{d^2x_2}{dt^2} = \frac{k_2}{M_2}\left[-C_A\left(2\frac{dx_2}{dt} - k_1\frac{dx_1}{dt} - k_3\frac{dx_3}{dt}\right) - K_A\left(2x_2 - k_1x_1 - k_3x_3\right) - F_{F2} + F_{A2}\right]$$
$$\frac{d^2x_3}{dt^2} = \frac{k_3}{M_3}\left[-C_A\left(2\frac{dx_3}{dt} - k_2\frac{dx_2}{dt} - k_4\frac{dx_4}{dt}\right) - K_A\left(2x_3 - k_2x_2 - k_4x_4\right) - F_{F3} + F_{A3}\right]$$
$$\frac{d^2x_4}{dt^2} = \frac{k_4}{M_4}\left[-C_A\left(\frac{dx_4}{dt} - k_3\frac{dx_3}{dt}\right) - K_A\left(x_4 - k_3x_3\right) - F_{F4} + F_{A4}\right]$$

These equations represent the acceleration of each module, which is the basis of the dynamic model and simulation of Badger. The constants k_1, k_2, k_3 and k_4 represent the clamps used to secure the position of individual modules during drilling. In this representation the constant is given a value of 0 when the clamp is engaged and a value of 1 when the clamp is released. This allows the appropriate dynamic combinations to be activated during the simulation of the drilling process.

To aid the simulation process of this robotic system, the dynamic model can be represented in standard state space form in the following manner:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}$$

Here the state derivative vector, $\dot{\mathbf{x}}$, contains the accelerations and velocities i.e.

$$\dot{\mathbf{x}} = \begin{bmatrix} \frac{dx_1}{dt} & \frac{d^2x_1}{dt^2} & \frac{dx_2}{dt} & \frac{d^2x_2}{dt^2} & \frac{dx_3}{dt} & \frac{d^2x_3}{dt^2} & \frac{dx_4}{dt} & \frac{d^2x_4}{dt^2} \end{bmatrix}^T$$

and the state vector, $\mathbf{x}$, contains the velocities and relative positions of the modules i.e.

$$\mathbf{x} = \begin{bmatrix} x_1 & \frac{dx_1}{dt} & x_2 & \frac{dx_2}{dt} & x_3 & \frac{dx_3}{dt} & x_4 & \frac{dx_4}{dt} \end{bmatrix}^T$$

These can be regarded as the outputs from the dynamic model. The input vector, **u**, represents the actuator and friction forces imposed on each module i.e.

$$\mathbf{u} = \begin{bmatrix} F_{A1} & F_{F1} & F_{A2} & F_{F2} & F_{A3} & F_{F3} & F_{A4} & F_{F4} \end{bmatrix}^T$$

These can be regarded as the inputs from the dynamic model. The resulting system matrix, **A**, can be represented thus:

$$
\mathbf{A} = \begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
-\frac{k_1 K_A}{M_1} & -\frac{k_1 C_A}{M_1} & \frac{k_1 k_2 K_A}{M_1} & \frac{k_1 k_2 C_A}{M_1} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
\frac{k_1 k_2 K_A}{M_2} & \frac{k_1 k_2 C_A}{M_2} & -\frac{2k_2 K_A}{M_2} & -\frac{2k_2 C_A}{M_2} & \frac{k_2 k_3 K_A}{M_2} & \frac{k_2 k_3 C_A}{M_2} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & \frac{k_2 k_3 K_A}{M_3} & \frac{k_2 k_3 C_A}{M_3} & -\frac{2k_3 K_A}{M_3} & -\frac{2k_3 C_A}{M_3} & \frac{k_3 k_4 K_A}{M_3} & \frac{k_3 k_4 C_A}{M_3} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & \frac{k_3 k_4 K_A}{M_4} & \frac{k_3 k_4 C_A}{M_4} & -\frac{k_4 K_A}{M_4} & -\frac{k_4 C_A}{M_4}
\end{bmatrix}
$$

Also, the input distribution matrix, **B**, can be represented thus:

$$
\mathbf{B} = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{k_1}{M_1} & -\frac{k_1}{M_1} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{k_2}{M_2} & -\frac{k_2}{M_2} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{k_3}{M_3} & -\frac{k_3}{M_3} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{k_4}{M_4} & -\frac{k_4}{M_4}
\end{bmatrix}
$$

Naturally, the turning dynamics of Badger will be dealt with in a similar manner and have a similarly structured state space representation.

Validation of this model will involve a 2 stage process. Firstly, the particular parameters in the model will be determined through validation against the scale prototype KIT experiemental response and system specifications (see Section 5 below). As data regarding Badger is obtained, the second stage validation of the model will use this data to obtain a dynamic model of Badger.

3.5 Complete Model

The complete model made up of four modules. The interaction between each module is dependent on the motion profile or gait selected. There are three motion profiles:

- Discrete

  The drilling is not continuous. After drilling a set distance, the drilling stops and each module moves forward to a rest position (all actuators retracted)

- Quasi-Continuous

The drilling is not continuous. The drilling stops but for a shorter time period than that of the discrete movement profile. The modules move as one with potentially different actuator velocities. The time period is dependent on the clamp extension and retraction time.

- Continuous

  The drilling is continuous and the motion of the modules is designed so that there is always a force being applied to the drill head module.

The inputs to the overall model are defined as:

- Translational Actuator Force inputs
- Rotational Actuator Force inputs
- Drill head RPM
- Environmental Inputs
  - Co-efficient of Friction for substrate being drilled
- Drag Force created by Umbilical cord

The actuator forces are the inputs to the complete model to allow different actuators to be modelled and experimented with.

The outputs of the overall model are defined as:

- The x, y and z position of the CoG, Drilling tip and umbilical connection of BADGER
- The roll, pitch and yaw of the CoG, Drilling tip and umbilical connection of BADGER
- The x, y and z position of the CoG and Actuator tip of each module
- The roll, pitch and yaw of the CoG and Actuator tip of each module
- The translational and rotational velocities of the CoG and Actuator tip of each module
- The translational and rotational velocities of the CoG and Actuator tip of each module

As the model progresses and the actuators form part of the complete model, the inputs of the system will change to be:

- Translational Velocity of BADGER
- Direction of travel of BADGER

The controller is not included as part of the BADGER model.

4. Simulation

This section provides a top-level description of the simulation that requires to be built around the model developed. Initial results are also presented.

4.1 Simulation framework

The simulation flow is presented in Figure 7.

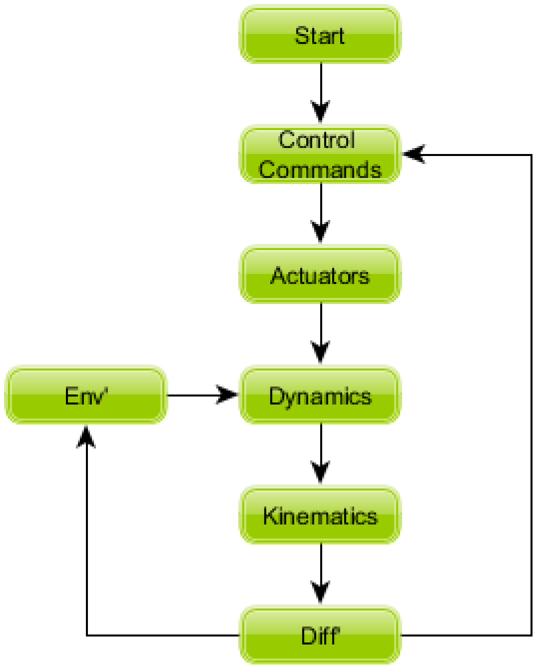


Figure 7: Simulation Flow

The flow starts with the commands being issued to the actuators. There will be a controller, developed later in the project, at this point, which will convert the desired BADGER velocity and direction into suitable actuator control signals. The outputs from the actuators will be applied to the dynamic model of the BADGER system. From this, the kinematics will be updated. The outputs from the model (both translational and angular accelerations, as well as velocities) will be differentiated using a suitable method, such as the Runge-Kutta method. This method has proved to be a suitable method when used in previous projects.

The environmental model provides the input from the ground friction. The model requires information about the current state of the BADGER and inputs regarding the current surrounding environment. The environmental model will be developed as the system tests progress.

4.2 Basic Simulation Results

To demonstrate the basic operation of the system a simplified simulation approach was carried out. The actuators were set to constantly move at a steady velocity until full extension, at which point the actuators then fully retracted. As each actuator reaches full extension or retraction, the next actuator begins its motion.

The pitch and yaw motion has not yet been modelled. The linear progression of BADGER can be shown as Figure 8. The point being traced here is the tip of the drill bit that is shown to be going forward using the control methodology set out above. This shows that the fundamental motion can work.

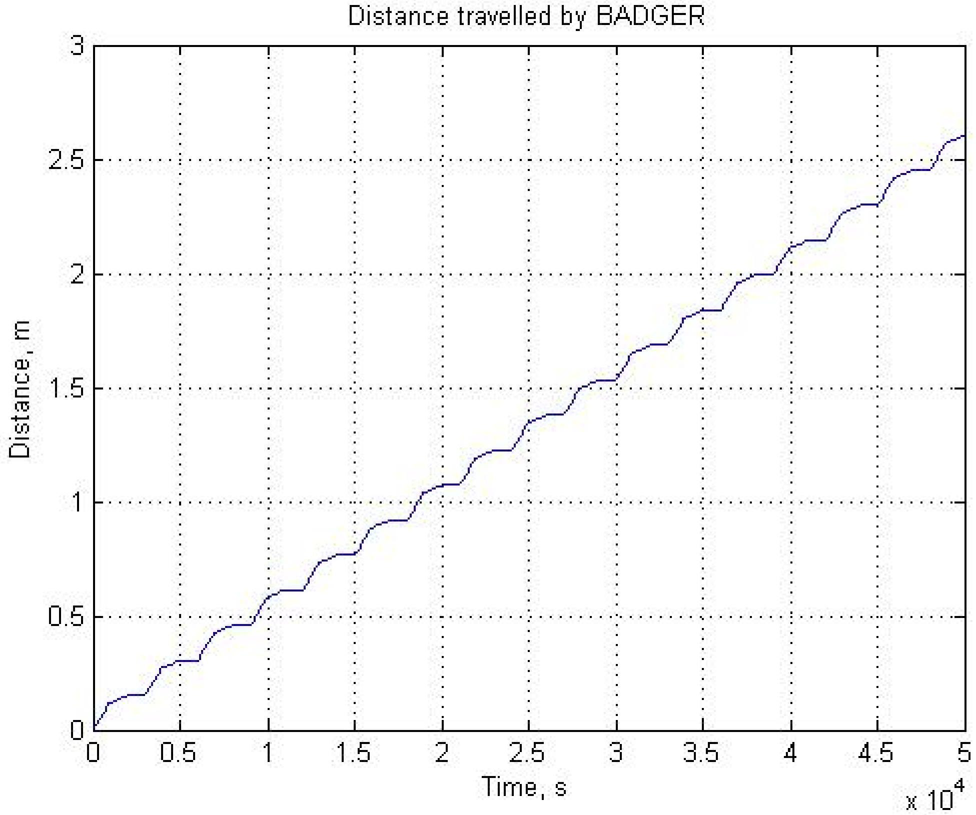


Figure 8: Linear Progression referenced to the tip of the drill head

Figure 9 provides the motion of the individual linear actuators. The actuators can be seen to operate in a pattern. This is as follows:

1. Actuator 1 starts extending, pushing the module 1 forward.
2. Once at maximum extension Actuator 1 starts to retract with Actuator 2 starting to push forward Module 2.
3. Actuator 1 stops when fully retracted. Actuator 2 starts to retract when full extension is reached and actuator 3 begins pushing forward Module 3.
4. Actuator 2 stops when fully retracted. Actuator 3 starts to retract when full extension is reached and actuator 1 begins pushing forward Module 1.
5. Actuator 3 stops when fully retracted. Actuator 1 starts to retract when full extension is reached and actuator 2 begins pushing forward Module 2.
6. This process repeats from step 3

This process describes the Quasi-Continuous movement profile.

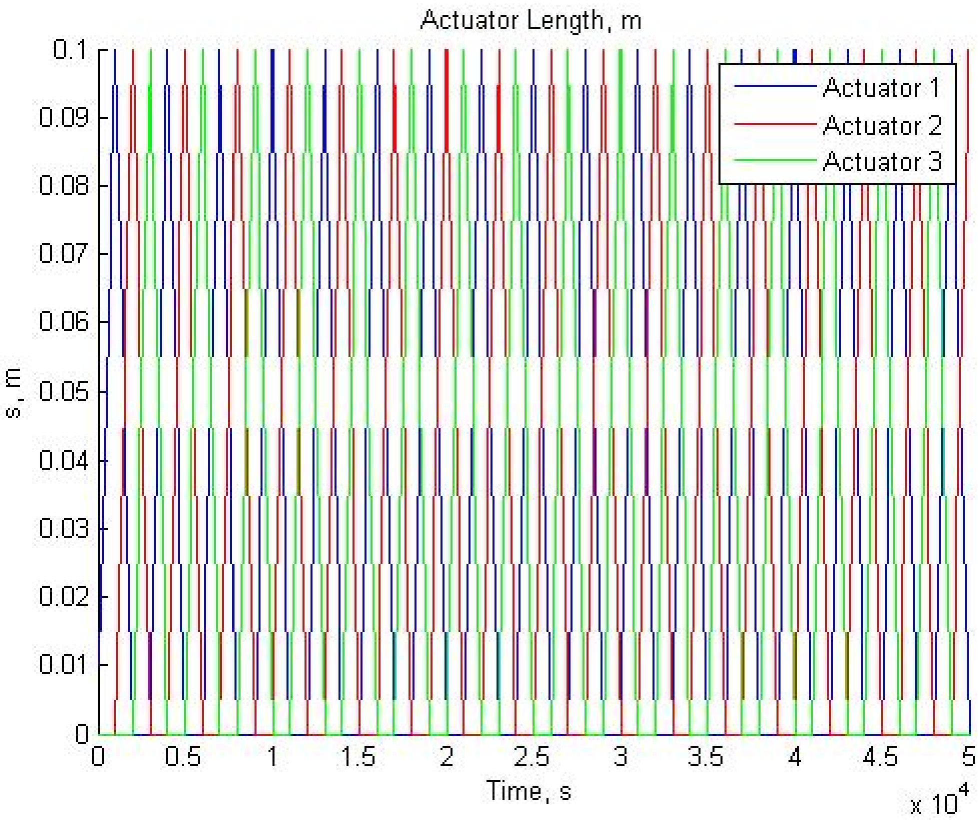
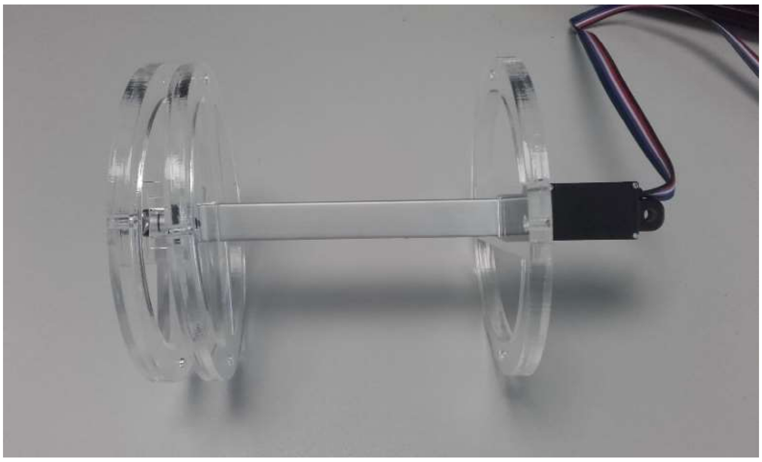


Figure 9: Actuator Position

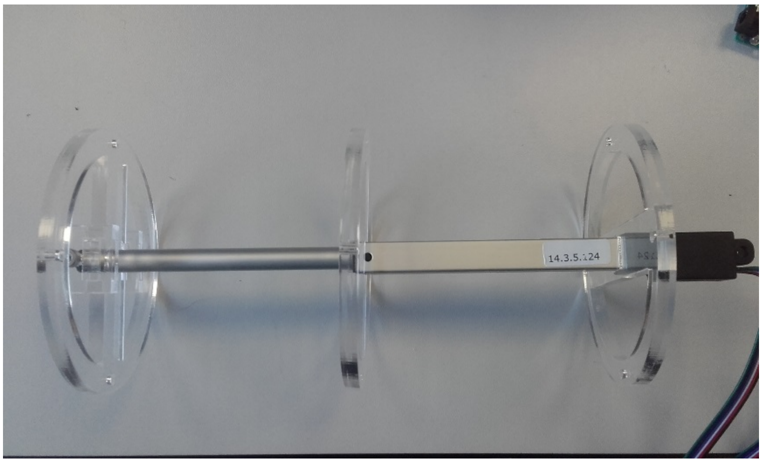
As stated, the current model is a very simplistic representation of BADGER however; the basic motion concept has been demonstrated using this model. The next stage of the development is to include the pitch and yaw elements of the design.

5. Kinematic Investigation Technology

To support the development of the mathematical model, the UoG has undertaken the development of KIT. KIT is a scaled version of the BADGER device with a 100mm diameter and an electro-mechanical actuation. Figure 10 provides an image of a module belonging to KIT, in both its retracted (a) and extended state (b).



(a)KIT module retracted



(b)KIT module extended

Figure 10: KIT Module

KIT will be used to support the iterative development of the mathematical model and can be used as a test bed to aid in the development of the controllers. The current model being developed is representative of KIT to allow the model to be validated against it. More on this process is described in Section 7.

KIT will follow the development of BADGER and will include all elements of the final BADGER device, albeit with a simplified drill head. However, KIT will not be as functional as BADGER; for example, the materials used will not allow it to drill (see Fig. 11).

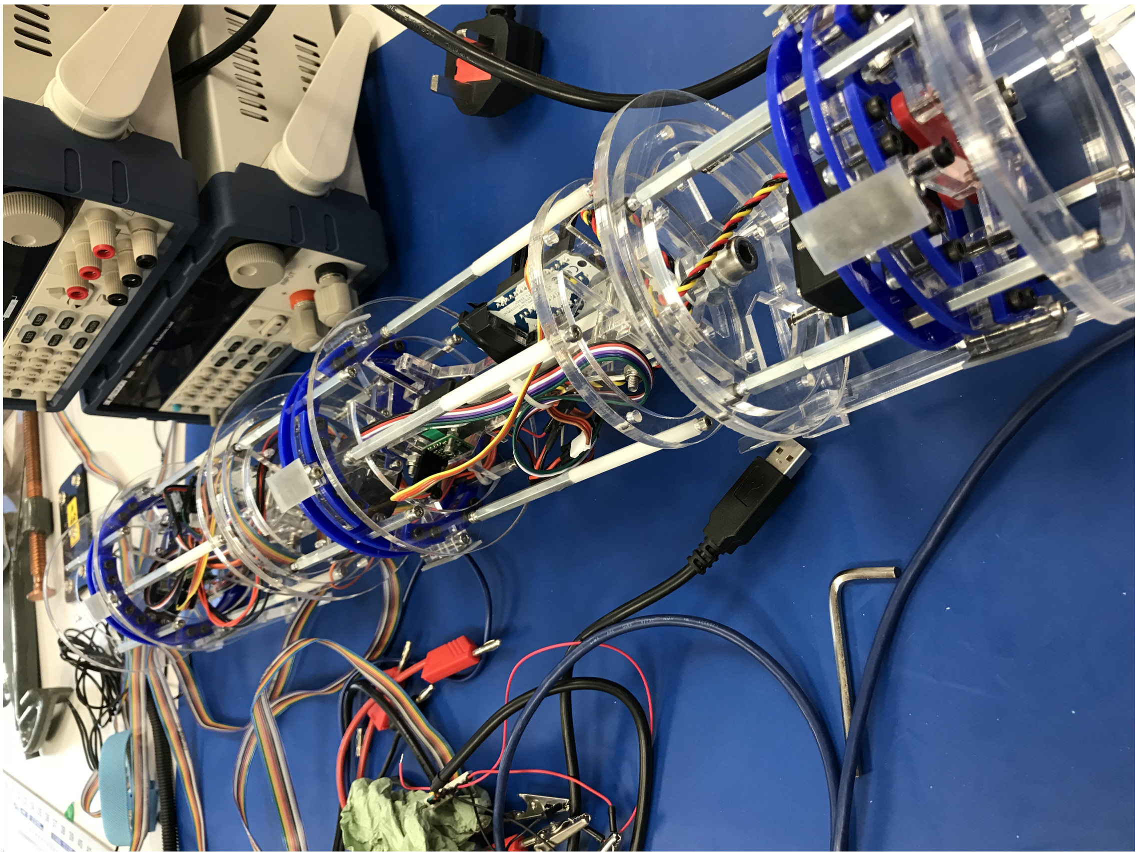


Figure 11: KIT System

6. ROS

An expected output from the mathematical modelling undertaken is a model of BADGER in ROS. A model in ROS will allow for development of localisation and mapping algorithms and run experiments within a visually simulated environment.

Currently a simple ROS model exists based on the basic movements of BADGER. This model has been developed by SILO. Updates to the ROS model will be carried out as updates to the mathematical model are made.

7. Continued Development

This section describes the continued development of the model of BADGER. The model of the system requires it to be as accurate a representation as is possible. However, as design decisions are agreed and designs change, the model is required to reflect this. The model presented in this document is only a basic one on which the full model will be built on. Hence, the development of the model is iterative.

As discussed in Section 5, the basic movement of BADGER will be tested on KIT. The results from the initial KIT tests will be used to validate the basic structure of the developed mathematical model.

When the initial BADGER joint prototypes are available to test the joint model developed will be validated. Compared to the KIT joint module the mechanism of how the motion is achieved will change (from electro-mechanical to hydraulic), however the mechanics of the system will remain the same (three translational actuators used to provide translational movement, with an additional three translational actuators providing the pitch and yaw motion).

A set of tests will be developed to model the joint prototypes. The tests carried out will, concerning the translational motion will measure:

- the distance travelled by the actuators
- the velocity of the actuators
- force applied by the actuators

Moreover, the pitch and yaw angles will measure:

- the distance travelled by the actuators
- the velocity of the actuators
- force applied by the actuators
- the angle for various extension lengths of the actuators

These experiments will be repeated at least ten times to provide confidence in the repeatability of the system.

The data gathered from these tests will enable the model developed to be validated. This will result in a level of confidence that the simulated BADGER joint output will match that of the actual BADGER joint output when the same control signal is applied to both.

The method of external validation will form part of the research output of the project, namely the use of Inverse Simulation as a means of validating complex systems.

The approach to the overall model is to have separate models that are form the main model. As and when data is available on the behaviour of different elements of BADGER then model will be developed. This will then be included in the list of models to call when running the overall model.

The expected roadmap for the model development is shown in Figure 12.

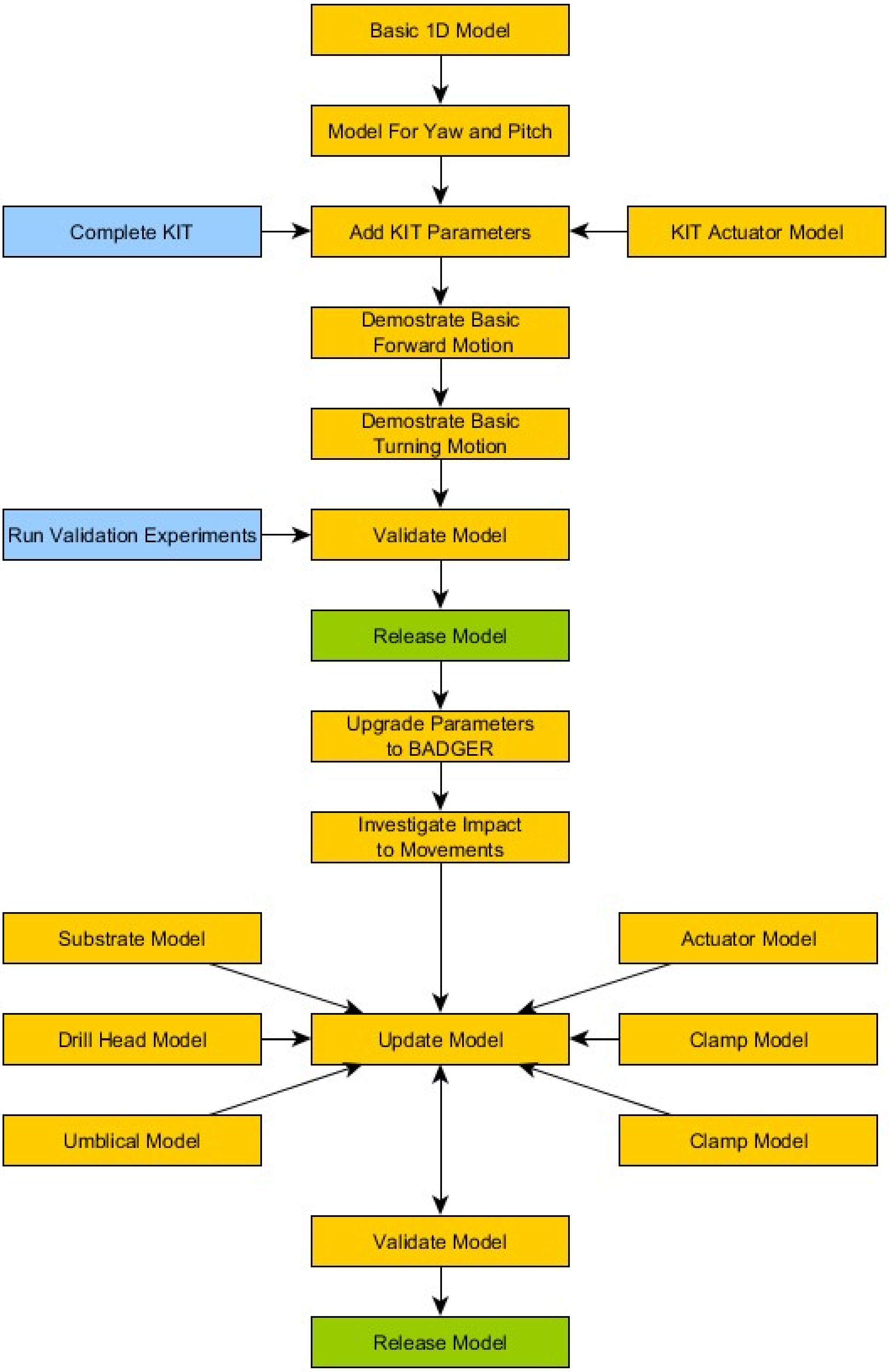


Figure 12: Mathematical Model development roadmap

8. Conclusions

This document has provided an overview of the mathematical model and simulation framework used to represent Badger and its actuator systems. How the model is to be used has been discussed, as has the current state of the model. A roadmap on the development of the model has also been presented.

References

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[3] Worrall, K., *Guidance and search algorithms for mobile robots: application and analysis within the context of urban search and rescue*, PhD Thesis, University of Glasgow, 2008