Terramechanics Based Traction Control of Underwater Wheeled Robot

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***Abstract* - The Bekker Theory of Locomotion has long been the leading applied theory when it comes to calculating and predicting soil-tyre interaction for terrestrial wheeled and tracked vehicles. Whilst the theory is applicable for terrestrial systems, there is no evidence to suggest it also applies under water. Furthermore, the complications of measuring the required soil parameters in marine substratum makes it difficult to apply. This paper explores the slip-based approach to the Bekker theorem and suggests an experiment designed to validate this theorem for underwater applications.**

I. INTRODUCTION

This project is being undertaken in collaboration with the City University of Hong Kong to fill a knowledge gap in the design formulation of mobile wheeled deep submergence research vehicles. Scientists as well as researchers are in need of an Underwater Unmanned Vehicle (UUV) that is able to traverse the seabed, regardless of configuration and type of substratum encountered. Preliminary research has shown that truly all terrain submersible vehicles will actually need three separate drive systems; wheels for flat and level areas of seabed, legs for negotiating rugged areas such as rocky outcrops and propellers or thrusters to negotiate large obstacles.

This team is designing semi-autonomous, highly agile, yet relatively simple underwater robot to be quickly deployed from a shore or a small vessel. The unit will be using compartmentalized construction, which allows spare parts to be carried and exchanged rapidly in-situ, maximizing the time underwater.

The vast majority of underwater seabed robots have tracks, which gives them very good traction and therefore high drawbar pull performance. These kinds of vehicles need a lot of power for maneuvering, so for extended mission profiles they would need an external electric supply. They also disturb the seabed to extent, which is unacceptable for sensitive marine areas and too time-consuming for researchers, as they would need to wait until the environment settles. Wheels may therefore be a more suitable alternative, particularly in low energy systems and where disturbance to the seabed is of concern.

Wheel behavior on terrestrial and planetary soils is an extensively researched topic, yet there has been very limited research done on traction and behavior of wheels underwater. It is not yet clear to what extent the terrestrial assumptions and equations are valid underwater. There is the difficulty of knowing how and when to take the hydrodynamic forces encountered close to the seabed into account. The other unknown factor is the trafficability, which is defined as capacity of soil to support a vehicle and sufficient traction for it. Furthermore, the various soil parameters needed to perform the calculations for slip and drawbar pull are very difficult to determine and measure underwater.

This paper focuses on comparison of different approaches to calculating drawbar pull and shows why one works better than the others. In order to validate the theoretical data with a set of tests, a small 4-wheeled test robot was built for the purpose of testing actual wheel behavior. The testing will be focused on different aspects of traction underwater and compared to existing, albeit terrestrial/planetary model. Due to unforeseen delays with the actual test rig, only work on the theoretical approach to analyzing traction mechanics has been done.

II. THEORETICAL BACKGROUND

A. Standard Bekker Theorem

The Bekker Theory of Locomotion has long been the established applied theory when it comes to calculating and predicting wheel-soil interaction for terrestrial wheeled and tracked vehicles. The theorem was initially formed by M.G. Bekker in the early 1950s' for military applications and was later adapted to predict the performance of numerous planetary wheeled/tracked vehicles. After extensive literature search, it was interesting to realize that very little research has been done to determine the wheel-soil interaction parameters that need to be refined to achieve optimum performance with regards to the design of wheel based robots for underwater exploration. This is even despite the proliferation of many different tracked and crawled UUV's done within the last 10 years.

The main vehicle performance parameter is the drawbar pull (DP), which is defined as net traction force - difference between soil thrust and motion resistance of the vehicle. Bekker [1,2] and later Wong [11] focused on establishing a numerical method for calculating DP from relation between normal and shear stresses under the wheel. Through the years, other analytical models to calculating DP have been developed, including Janosi et al [7], who modeled DP as a function of a wheel slip and Yoshida and Ishigami [9], whose model focuses on slip and lateral forces on the wheel to calculate DP.

Initially it was decided to review the standard Bekker theorem and the derivation of it, so it could be modified or adapted to the terramechanical model that applies to wheels for underwater use. A detailed study involved with the theorem showed that the approach developed by Bekker and by Wong was too involved with amount of required soil parameters to be determined. The standard calculation for drawbar pull is:

$$DP = H - \sum R \tag{1}$$

where H is soil thrust and R is motion resistance of the vehicle. Motion resistance can be further expanded,

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$$R = R_c + R_b + R_g + R_{other} \tag{2}$$

where R_c is soil compaction resistance, R_b is bulldozing resistance and R_g is gravitational resistance. Fully measuring these parameters, without an existing database to compare with was considered too costly and time consuming. To calculate only the bulldozing resistance (3);

$$R_b = \frac{B\sin(\alpha+\varphi)}{2\sin\alpha\cos\varphi}(2zC_0k_c + \gamma z^2 k_y) + [\frac{\pi\gamma l^2(90-\varphi)}{540} + \frac{\pi C_0 l^2}{180} + C_0 l^2 \tan(45+\frac{\varphi}{2})]$$

A total of six soil parameters are needed:
φ -Soil Internal Angle of Friction
γ - Soil density
C_0 – Cohesive strength of soil
k_c - Modulus of cohesion of soil deformation
k_γ - Modulus of density of soil deformation

The rest of the calculations follow similar trend with respect to soil parameter requirements. As planetary robotics faces similar problems with regards to unknown terrain and strata, it was clear that whilst the Bekker theorem is a valid and correct model, it may not be practical since some of the parameters needed to calculate variables were difficult or involved to determine.

B. Slip-Based approach

Yoshida and Ishigami detailed and tested an improved and practical model of Bekker theorem for planetary rovers. In this approach drawbar pull is calculated from its relation to the slip ratio. When wheels spin, the action of spinning will remove the substratum from under the wheel, and it will sink into the stratum. From this dynamic sinkage, slip ratio can be modeled. The drawbar pull is calculated as:

$$DP = rb\int_{\theta_r}^{\theta_f} \tau(\theta)\cos\theta\, d\theta - \int_{\theta_r}^{\theta_f} \sigma(\theta)\sin\theta\, d\theta \tag{4}$$

where *σ(θ)* (normal stress under the wheels) and *τ(θ)* (shear stress under the wheel) can be determined from the following equations;

$$\tau_{(\theta)} = c + \tau(\theta)\tan(\phi)(1 - \exp\frac{-r}{k}[\theta_f - \theta - (1-s)(\sin\theta_f - \sin\theta)]) \tag{5}$$

$$\sigma(\theta) = \sigma_{max}[\frac{\cos\theta - \cos\theta_f}{\cos\theta_m - \cos\theta_f}]^n \tag{6}$$

θ_m - angle at which maximum stress is observed and σ_{max}- maximum normal stress are determined from the following derivations;

$$\theta_m = c_1 s \theta_f \tag{7}$$

$$\sigma_{max} = (\frac{k_c}{b} + k_\phi)(r)^n(\cos\theta_m - \cos\theta_f)^n \tag{8}$$

From the following equations, θ_f – wheel entry angle and θ_r - wheel exit angles are obtained;

$$\theta_f = \cos^{-1} 1 - \frac{(h_s - h_k)}{r} \tag{9}$$

$$\theta_r = c_3 \theta_f \tag{10}$$

Kinetic sinkage in steady state; h_k is determined by:

$$h_k = c_2 s \tag{11}$$

and h_s - static sinkage from:

$$h_s = r(1 - \cos\theta_s) \tag{12}$$

From testing observations, vertical load W and slip ratio can be determined, and Θ_s – static contact of the wheel calculated from:

$$W = \int_{\theta_s}^{-\theta_s} ((\frac{k_c}{b}) + k_\phi)(r(\cos\theta - \cos\theta_s))^n rb\, d\theta \tag{13}$$

The variables needed to calculate drawbar pull (DP) are slip and vertical load. These can be measured when tests with specifically constructed experimental underwater robot are done.

III. EXPERIMENTATION

The experimentation was designed to prove that the slip-based approach is applicable in underwater robot design. The experiments will be conducted in a controlled environment, in a large 2m by 1.2m tank. The bottom will have approximately 15cm base of substrata for testing. Seven different mixtures of seabed material will be used, which will give rough overview of what is expected to be encountered on the seabed. Different types of seabed material will be made by mixing local sea sand with mud from in the following rations:

- 100% sand, 0% soft silt.
- 80% sand, 20% soft silt.
- 60% sand, 40% soft silt.
- 50% sand, 50% soft silt.
- 40% sand, 60% soft silt
- 20% sand, 80% soft silt.
- 0% sand, 100% soft silt.

Currently determining the parameters (shear and compressive strength) of the soil is not going to be possible, however samples will be kept for future references. Each experimental run will be carried out for 10 successful times and the average result used as the experimental result. Two sets of tests are planned to help validate the theoretical models.

Firstly, the robot is going to be run on all variables of the stratum to observe if wheel behavior is as predicted. Waldmann and Lutz [10] have observed in their tests that the wheel performance was less than expected, with the wheels having tendency to dig in, possibly due to weak soil cohesion. The experiments when compared to theoretical results will show whether the Ishigami model is applicable for describing wheel behavior on substratum. What will also be determined is the extent that hydrodynamic forces act in the wheel-stratum interaction.

This experimental setup will also allow the observation of other parameters and situations, for example bulldozing and digging in to be observed close-up, including the initial conditions required. The effect of buoyancy on the robot should have a dramatic effect on the performance.

The experimental setup proposed will allow this to be further understood.

IV. CONCLUSION

The use of wheels as the main drive for Unmanned Underwater Vehicles (UUVs) offers many advantages over the more conventional thruster driven units. The stable working platform, the prospect of parking it while collecting information and the ability to relocate positions repeatedly and easily are a few.

Tried and proven engineering and technology is widely available to build underwater rovers; however, the optimization of designs has not been investigated thoroughly to ensure that such underwater vehicles have maximum performance. This is not the case for topside terrestrial rovers, which have even been specifically designed and built for their respective planetary conditions. This paper investigates Bekker Theory, the applicable standard theory for wheel - soil performance, and the sections of this theory that could apply to underwater environments.

The key difficulty with the practical application of this model is the determination of the multitude of soil parameters required in order to be able to calculate important key parameters like drawbar pull. It may be relatively straightforward to measure these for terrestrial soils, but doing so underwater offers a whole new set of challenges. Drawbar pull and efficiency are the key factors in designing for maximum performance.

It is possible to analyze wheel - substratum parameters by considering more complex factors like slip and wheel sinkage. These parameters are easier to measure underwater and the Yoshida – Ishigami model has shown that there is an alternative on how to calculate the Drawbar Pull that may be applied to rovers in the underwater environment. This paper explains this version and details an experiment that may be used to confirm the theorem is applicable.

The experiment will verify the suitability of the Yoshida – Ishigami approach for underwater wheeled robots. It will also verify certain methods that can be used to obtain the raw values needed for the calculations. This includes adjustable constant speed drives and the location of specific marks for measuring parameters such as sinkage. Since both sinkage and slip are physical parameters they can be measured using electronics sensors. Slip, for example, can be measured using an ultrasonic speed sensor mounted in front of the robot. The results can then be compared with the calculated speed from the rotation of the wheels.

Sinkage can also be measured electronically by sensors mounted on the robot to measure the distance to the substrata. The information could be fed into buoyancy-controlled device that could be tuned to allow maximum efficiency for all condition. This includes trying to minimize bulldozing and digging in. The technology involved in doing this is already available, however the data required to determine the optimum performance is not.

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