CONEM 2016
CONGRESSO NACIONAL DE ENGENHARIA MECÂNICA
21 - 25 AGOSTO DE 2016 FORTALEZA - CEARÁ
ABCM 40 anos – Associação Brasileira de Engenharia e Ciências Mecânicas

FRICTION CONSIDERATIONS ON AN APODAL ROBOT MOVEMENT

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Abstract: *The greatest difference between traditional and modular robotics is the ability to adapt to different and unexpected situations. Among them, the apodal types get a lot of attention. The apodal movement pattern came from snake observation and studies and have been applied to large number of called Snake Robots prototypes. But still, a perfect reproduction of the biological movements are still to be reached. One of the principal problems rest on a proper friction reproduction. Snake movement relies heavily on their anisotropic skin and flexible body. This paper looks into friction models already proposed, the literature of snake locomotion and search for structural solutions to be applied on a modular robots in order to reproduce an anisotropic friction model.*

Keywords: *modular robot, snake robot, friction, anisotropic friction, snake movement*

1. INTRODUCTION

Studies in robotics are made in order to assist humans, going from industries to surgical rooms or conflict zones. Shortly, robots are made to do thing easier and safer. That being said, its only natural that there are several ramifications of robots, made for different tasks. The ones this paper will care about are pretty similar: modular and snake robots.

Both are supposed to be robust, versatile and capable of dealing with obstacles and unfriendly situations. The main difference between them is that while the ideal modular robots would be able to be auto reconfigurable (changes it's geometry without humans interfering) with all modules independent, the ideal snake robot would be capable of reproduce the behavior of an actual snake.

However, the first said modular robot, CEBOT, by Fukuda *et al.* (1989), was also refereed as the "modular snake robot". In fact, most of the modular robots have apodal movement (based on combinations of pitch and yaw), some following what is called the "serpenoid curve", which analysis can be found at Gomez, (2008).

That being said, it's not a surprise that the Ereko Group (University of Brasilia - UnB), which started focusing only at the principles of modular robotics and modular robots prototypes, as seen in Souza *et al.* (2011), ended going further into snake locomotion at each new project. At first, the main focus were only to achieve a pitch-pitch movement (from ErekoBot Alpha in 2011 to Erekobot Sigma, during 2014) but the two latest project (Sigma Lily, from 2015, and Neke Project, still on design phase, being those the ones refereed on to this paper) have actually being designed for more complex combination (like pitch-yaw), resembling more the actual snake models.

During simulations and comparison with real case results, a question arose: how much does the friction affects the movement? It's a well know fact that friction force is the main point of snake locomotion. While most of vertebrates movement rest on inertia and momentum, for some evolutionary reason, snakes relies on manipulations of the friction force.

Such conclusions may sound obvious, since without friction there is no movement, but in general there is no friction is just ignored or roughly approximated. You just need to know how much force is needed for that the static friction goes into dynamic.

But as one searches about that, more obvious it becomes that friction is something that have being neglected not for being too simple and forgettable, but for being too complex. It is not hard to found papers about efficient loss on roboticarms because of energy dissipation due to friction between joints, neither is to find studies about precision lost on robot control for the same reason. And still, it is hard to find friction models applications in real case scenarios studies.

This paper shows a review of friction models and snake locomotion studies, looking for the best solution in snake robot friction modeling, in order to find a proper model to be applied and tested on the Ereko Group robots.

2. FRICTION

2.1. Friction History Review

The most known friction laws are empirical and the actual effects of friction force depend so much on the state of the contact surfaces that is near impossible to state a proper general model. An ordered review, as made in Geffen, V. Van. (2009), can be very enlightening when trying to not only understand but also use mathematical and physical tools.

One of the first to state about friction laws was Guillaume Amontons, in 1699. He observed the resistance to sliding movement and how it was affected by a normal applied force. He defined the concept of "coefficient of friction" and said that the friction in not related with the area of contact.

The historical facts were compiled from physics textbooks (Halliday, 1983; Nussenzveig, 2002; Ramalho, 1997).

Coulomb, in 1785, was the one who noticed the relation between the friction force and the velocity of the movement, one of the main problems when modeling, since it causes a discontinuity when the velocity equals zero. His results leaded to the division between the case of "static" and "dynamic" friction. Coulomb's model can also be said as a "perfect dry friction model".

As materials and atomic-scale studies advanced, the relation between friction phenomena and the body behavior (deformation, plasticity, hysteresis) became more clear. The notion on non-perfect surfaces and further studies into anisotropic cases increased the complexity of friction formulation, but also leaded the path to better models.

In the search for accurate friction models, a new branch arose around 1990: physics-motivated models. They define three different levels: atomic-molecular, asperity-scale and tectonic-plate. As the empirical bases models tend to be very restricted, the physical ones look for more general applications, more about prediction of nature phenomena (earthquakes and lightning) than simulation and control.

Research on animals locomotion and bio-inspired equations of movement – like the serpenoid curve proposed by Hirose on 1993- showed how important friction manipulation can be. It also brought up the question of anisotropic friction: real animals body surfaces aren't perfect and so their gaits can not be fully explained by the usual models.

It became clear that there is no such a thing like a general friction force description equation, and that the friction phenomena, up to this days, is way too dependent of the case parameters for a proper approximation in most cases.

2.2. Friction Cases

Most of forces described on basic mechanical physics courses are continuous and their phenomena is rather simple. The gravity force, as an example. It has a proper formula that describes the phenomena, proposed by Isaac Newton and can be resumed into bodies being more or less attracted by each other.

On those said courses, the friction force is simplified as an external force applied on the contact surface on the opposite direction of the force responsible for the incoming movement. It's the friction that stops a box from going down a ladder due to it's weight force.

The friction phenomena, however, as explored by some studies - as in Al-Bender, (2010)-, has at least three states: static, dynamic and the transition between those two. This comprehension will be important into the models explanation on next section. Between those, there are some observable effects that can be observed. Most cases, they are just ignored on the models, or approximated by a simplification.

2.2.1. Stick-Slip

In modeling it's considered a dynamic friction case, but it's easily observed into real life -common in robotic actuators. It occurs at low velocities and it's associated at non-linear friction. It can be described by a non-smooth transition between static and dynamic: the body suddenly starts to move forward. Sometimes it also occurs during movement, when the contact surfaces stick to each other. It is a discontinuity and causes oscillations in the movement, but can be prevented with lubrication. Even if it does not look relevant to the snake locomotion simulation – can be approximated as instantaneous transition - the motors on the robot modules can be affected, lowering the precision and efficiency of the movement.

2.2.2. Stribeck Effect

States that the friction resistance depends smoothly and inversely on velocity. It's observed in dry-friction cases – poor lubricated situations. It can be explained on atomic level by materials science, can be explained as an lubricant layer that lessens the friction when the surfaces start relative motion and introduces the concept of Stribeck Velocity.

2.2.3. Pre-Sliding

For small displacements, relates to hysteresis – internal damping of the material. Is defines a zone with micro-displacements due to microscopic asperities. Those asperities rises the friction force by deflecting, working pretty much like stick-slip effect and adding a lag on transition between static and dynamic friction. It only makes sense one dynamic friction models.

2.3. Friction Models

There are a lot of models on friction studies, but there is not a single formula able to explain all the phenomena involved. Most of time, the models have so many constraints and variables in order to be valid that they can just be applied to a short range of cases. It's not rare to found whole studies around certains models for cartains applications, as in Romano, R. A. (2008). All the solutions for the models are numerical, since all of them have to deal with the discontinuity of the friction force.

As said before, on the historical context of the friction force, one of the greatest contributions of friction modeling came from Coulomb. However, his equation (also known as Dry Friction) goes to zero when the velocity does. In mathematical terms, this is a discontinuity and it´s, therefore, the big problem on friction modeling.

This section will review the most known friction models, their inspiration and mechanical of them, looking for better comprehension of how they were developed, what considerations do they have. For all cases, "velocity" refers to relative velocity between the contact surfaces. It's assumed steady-state of velocity.

No formula is showed in here, since the main objective is just to introduce and unravel their inspirations, ultimately looking for an applicable model for the prototypes from Ereko. Further mathematical formulation can be found in the reference papers from ,Zailmann, A., Dupont, P.(1990) and Curnier, A. (1984).

2.3.1. The Basis: Coulomb and Viscous Friction

Both are the most basic in each environment (dry and viscous contact).

The Coulomb model relates the friction force with the normal force, the velocity of the body and the friction coefficient. Even if the normal force can be defined pretty easily, just as the velocity, the friction coefficient is an empirical value that depends of material and geometry, for the body and for the surface of contact. In other words, it depends on data to be applied. Also, the same exact scenario have different coefficient for static and dynamic situations. Same goes for the Viscous model, but there the data in just for the fluid, for it's viscous friction coefficient.

Just looking at the equations anyone could say that the friction force has a linear relation with the velocity, but it's not like that. In fact, there is a small reduction of the friction, due to the Stribeck effect.

Those two models already shows the velocity problem: once it goes to zero so does the friction force, what any simple experiment of pushing some near object can prove wrong. To solve that you assume a different equation and different coefficients when dealing with a static friction case.

In a most real case scenario, the total friction force should be the sum of both models. It's said "most real" because in real real cases scenarios it should be considered the deformation of the contact surfaces and the possible displacement of part of the environment, like in case of sand or mud.

2.3.2. Looking for Better Simulation: Karnopp and Leine

In order to solve the problem of the zero velocity in simulations, Karnopp gone for a very mathematical approach: he defined a neighborhood where a said thing is true. In this case, since there is no velocity in this small neighborhood, the friction force would be only function of the force applied on the body. Once there is movement, the velocity comes back to the equation. His model still lacks numerical stability, but is largely cited in control studies. It have also been used in friction compensation analysis.

Using the same logic of separate the friction in neighborhoods came Leine, with the proposal of three different ordinary equations, for stick, slip and transition phase.

2.3.3. Putting Them All Together: The Seven Parameters

All the four models described before are cases of static friction models, and when looking at them it becomes quite clear that the friction force is not a single smooth continuous force, but rather a contributions of different effects and phases. So, this model tries to put all the pieces together. Each of the seven parameter is actually an aspect of the friction phenomena. Coulomb, Viscous, Stribeck effect, the surface stiffens and so on. It gets all the know variables and adds time, getting a dynamic model which is dived into Stick and Sliding phases. However, for such a complete hypothesis, it still lacks in results. It's overly complicated for under results.

2.3.4. Stress-Strain and Plasticity: Spring Behavior for Dahl And LuGre

The friction force has phases and effects, as said before. Also, there are material science studies that proves that friction is related to deformation of contact surface. Now, think about the friction force as a body, mostly a spring, and take resistance of material and vibrations principles. Then, for small displacement, where the displaced object goes back to it's original position, Dahl said what was occurring was equivalent to an elastic material deformity. For larger displacements, there would be a plastic deformation and therefore a permanent displacement. With this logic, the transition force necessary to go from static to sliding behavior is equivalent, in concept, to the maximum stress in a stress-strain analysis.

With that, Dahl made a formulation enveloping Coulomb's Force to model a Friction Force with considerations of per-sliding and hysteresis.Dahl does not consider the stick-slip effect, nor the Stribeck, so this model has a loss on performance for low velocities. LuGre, on the other hand, consider Stribeck and pre-sliding.

LuGre cames from Dahl, but instead of using the Coulomb's Force he defined a generic velocity-dependent function that added a damping associated with microdisplacement and a component for internal friction state, associated to the deflections of asperity cited on Pre-Sliding definition. This model can be user for asymmetric friction cases.

3. SNAKES

3.1. Basis of Snake Locomotion Gaits

Snakes have different gaits for different purposes. When dealing with robot simulation, all of them can be simplified and transmitted as equations of movement. However, since the current snake robots does not have all the resources that a real snake count on, the result of the bio-inspired movement will not be perfect, as concluded in Liljeback, (2012).

On Tab. 1 all the known snake gaits are listed with a brief explanation that makes easier to see why they work. Most of the information below was gathered by the studies on snake robot development from Liljeback *et al.* (2011)

All of the showed gaits are only possible due to the snake's anatomy. Their anisotropic friction condition, as an example, is given by their scales and thus grants a larger friction coefficient on transverse direction in comparison to tangential. Also, it's proved that snakes can change their scales configuration – stretching the body and thus increasing the space between them or bristling them – according to their purposes. Some studies also shows that snakes have a pressure-sensor like system of their skin, that gives them a feedback of the external forces applied on their body and thus allow them to choose the best configuration for that one environmental situation.

Table 1. Snake Locomotion Models.

Gait	Utilization	Body Behavior	Surrounding Interaction	How it Works
Lateral Ondulation	Non-slip terrains, underwater	Wave propagation, starting from head and going through the body	The snake pushes it's body against irregularities on the ground – or against the water resistance when underwater	There is no static contact at any point between the snake and the ground. Uneven weight distribution along body to keep some parts off-ground
Concertina Locomotion	Narrow spaces with limited movement range	Part of the body is curled while the rest is extended. The curled part works as an anchor	The snake uses the walls of the environment and its natural anisotropic body to extend itself forward	The curled part of the snake makes use of it's high static friction coefficient to anchor it's body while other part is extended
Rectilinear Crawling	Usually before lunge, linear and silent movement	Extend and contracts different parts of the body	Can be used in any kind of ground, but it requires a certain level of irregularity to grip the scales	The extension of the body increases the gap between the scales, and the snakes uses them like hooks, fixing itself to the ground and pulling the once contracted part of the body

3.2. Snake Friction Results On Literature

There are two main options to deal with the real case anisotropic friction of snake skin: simulate an actual anisotropic friction surface state or apply Sideslip Constraints.

Sideslip Constraints are easier to simulate, less complex. Shortly, they assume that the robot's links will not move sideways. Such situation is achieved mostly by installing wheels in the tangential direction of the links. Even if it is a valid solution, it goes against the objective of develop a proper robot capable of realize all the Snake Locomotion Gaits previously cited.

Therefore, Sideslip Constraints will not have a further consideration in this paper.

On I. Grabec,(2002), it is applied a anisotropic friction law in a simulated Snake Robot. It is defined a friction coefficient that is directly related to the resulting propulsion of the snake, propulsion gave, like in real snake case, by variation on body configuration. A vector for Friction Force is defined, applied on the root surface, resulting from interaction with the ground. It concludes that the friction is not perforce related to velocity. It rather considers the friction law as a problematic result, that it not worth further study, but just something to simplify analysis. But again, this considers only a creeping snake, with a movement that can be resumed into pitch-pitch case, which truly does not need friction consideration.

The work from Transeth A. *et al.* (2008) on the other hand makes use of the Coulomb's Dry Friction principles and add a list of considerations (anisotropy and also isotropic cases). This study get a way more complex case of snake locomotion, looking for simulation on different environment cases, which goes closer to the applications desires for Snake Robots, like search on havoc areas.

In studies showed on Hu, D. L., *et al.* (2009), David Hu demosntrates that this kind of movement depends heavily on the friction coefficient application and more, the dynamics that real snakes can give them. It also shows how the load distribution, already cited on Table1 affects the snake propulsion and velocity. It's a matter of efficiency.

In a more recent paper, Serrano, from M.M., *et al.* (2015), the snake-like robot is referred as "redundant", since the amount of attention gave to it on the past years, but it also brings how little has the friction problematic received. It goes down in proposing a prototype able to reproduce the scales of a real snake. It does not, however, rely on any known friction model. Rather, it does an empirical approach: experimentation, simulation, performance.

4. ROBOTS

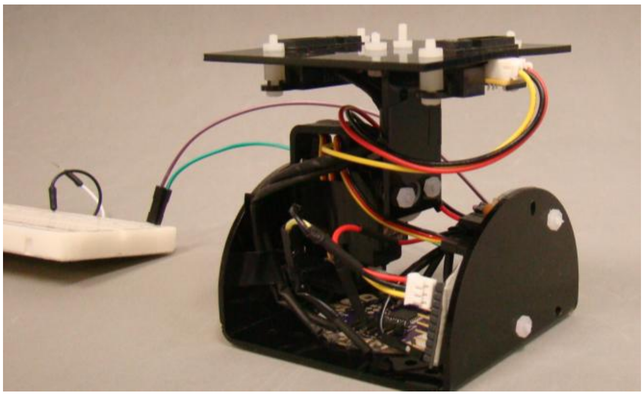
4.1. Ereko Group Review

The Ereko Group is a research group from University of Brasília (UnB) that started aiming the construction and operation of a functional apodal, snake-like robot**.**

4.2. Sigma Lily

The Sigma Lily prototype, showed in Fig. 1 was developed during the year of 2015. It's design is pretty similar to the first documented design (ErekoBot Alpha, 2011), composed of armor, actuator, linked to a lid by an arm.

Figure 1. Sigma Lily prototype with acrilic armor.



It is able to perform a pitch-pitch movement using locomotion equation defined by Gomez. The said pitch-pitch configuration is shown in Fig. 2.

For the Pitch-Pitch case there was a considerable deviation on the desired trajectory. This can be explained by a lack on torque force by the actuators, imperfections on the armor structure that gave the module instabilities and unexpected surface contact areas. The Pitch-Yawn configuration just did not worked, simulation or real case. Yawn-

Yawn, on the other hand, had the same result for both approached: the robot just kept sliding in the same place without any propulsion, pretty much like a snake on silk.

Thus, it was easy to conclude that: the current structure geometry was not the most adequate for the desired behavior; the module, even functional, lacked on stability study and actuators performance.

Figure 2. Sigma Lily in pitch-pitch configuration on flat ground.

In sum, the robot was a modular robot, indeed, but a modular robot that would need to go under review to go anywhere near Snake Locomotion.

4.3. Neke Project

From the mistakes noticed on Sigma Lily, a new project started: Neke, name that means "Snake" in maori language. Still under development, this robot goes closer to Snake Robots than any other previously developed by this group.

4.3.1. Geometry And Material

It started with a mostly cylindrical armor. Simulation, however, showed that a perfect circular cross-section did not give enough stability for any lifting movement – making any desired gait unfeasible. No lifting means no Sinus-Lifting condition for anchoring, no pitch-pitch movement in general.

The solution was to go closer to real snakes. That could mean two things, either going for a mode elliptical cross-section or defining a flattened ground surface. The decision was to made a more hexogonal-like armor. More inertial studies must be done before a final design, but simulations of the previous design with hexagonal rings for stability showed that this is a good path.

Even thought the PVC used on Sigma Lily gave good result, it's geometry was easier to model and reproduce, which is not true for Neke. In order to prevent construction errors and achieve not only a better stability control but also more reliable result from simulations and prototype testing comparison, it was decided that the armors will be confectioned using 3D Printer technology.

All the current simulations and estimates are done considering the material as ABS filament.

What is left is to decide how to make the anisotropic surface approach. So far, only dry friction cases are being considered. Even thought the work on Serrano gave good results, the scales will be done as a separated skin, for comparison purposes and also for a modular robot principle: it should always be versatile. The desired configuration is a snake robot with a low anisotropic friction surface with attachable and easily cambial rings for different ground situations.

4.3.2. Componentes And Their Influence

The electronic components are all embarked on the individual robots. None of them is just passive. This just goes together with the modular principles, but also means that each of them can end considerably heavy.

Also, as showed on Table1, about snake locomotion, weight distribution control is a main point. There are two case scenarios: the robot will either be supplied by batteries or by external power. Each of them ends in different Inertia Matrices for the module.

First step is to define all components in order to obtain a static stability for each module in order that it will not roll. Shortly, the components must be in such a way the once the module velocity is zero, it stays with no displacements.

It is already known that snake robot stability is a time-to-time variable. The equations of movement will need to go under severe simulation and review in order to be valid in this model.

5. CONCLUSION

A frequent question that came into discussion during Sigma Lily develop was if the friction was really this relevant. The prototype testing showed that it could be, not only for the snake locomotion gaits but also for friction compensation on the actuator.

This study showed that, yes, friction is that relevant. Once this was decided, it was necessary to decided which model should be used. Even if most of control and compensation cases uses dynamic and complex models, such as Dahl, it became clear that a simpler model does work. It just need adjustments, mostly with data obtained from performance comparison.

At the end of this paper all the desired question still left were answered. The review on Snake Robots and Friction Modeling allowed to define what are the next steps for a proper modular snake robot development.

6. ACKNOWLEDGEMENTS

The authors thanks CNPq, PROIC,DEG, DEX from University of Brasília for their support both financial and institutional.

7. REFERÊNCIAS

Al-Bender, F. (2010). "Fundamentals of Friction Modelling". ASPE Spring Topical Meeting on Control of Precision Systems, 117–122.

Curnier, A. (1984). "A theory of friction". International Journal of Solids and Structures, 20(7), 637–647.

Dupont, P. E. (1990). "Friction modeling in dynamic robot simulation. Proceedings"., IEEE International Conference on Robotics and Automation, 1370–1376.

Fukuda, T., Nakagawa, S., Kawauchi, Y., & Buss, M. (1989). "Structure decision method for self organizing robots based on cell structures-CEBOT". Proceedings, 1989 International Conference on Robotics and Automation, 695–700.

Gomez, J. G. (2008). "Modular Robotics And Locomotion: Application of limbless robots". Universidad Autonoma de Madrid, Ph.D. Thesis, 1 – 436.

Geffen, V. Van. (2009). "A study of friction models and friction Compensation.", Technische Universiteit Eidhoven, Departament Mechanical Engineering, Dynamics and Control Technology Group.

Grabec, I. (2002)." Control of a creeping snake-like robot." 7th International Workshop on Advanced Motion Control. Proceedings (Cat. No.02TH8623), 526–531.6

Halliday, D.; Resnick, R. "Física volume 4". (1983)Livros Técnicos e Científicos, Rio de Janeiro.

Hirose, S. (1993) "Biologically Inspired Robots: Snake-Like Locomotors and Manipulators", Oxford University Press, Oxford.

Hu, D. L., Nirody, J., Scott, T., & Shelley, M. J. (2009). "The mechanics of slithering locomotion." Proceedings of the National Academy of Sciences of the United States of America, 106(25), 10081–10085.

Le Tien, L., Albu-Schaffer, A., De Luca, A., & Hirzinger, G. (2008). "Friction observer and compensation for control of robots with joint torque measurement." 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS, 3789–3795.

Liljeback, P., (2011)."Modelling , Development , and Control of Snake Robots", Norwegian University of Science and TechnologyThesis for the degree of Philosophiae Doctor.

Liljeback, P., Pettersen, K. Y., Stavdahl, O., & Gravdahl, J. T. (2012). "A review on modelling, implementation, and control of snake robots." Robotics and Autonomous Systems, 60(1), 29–40.

Nussenzveig, H. M. "Curso de Física Básica 1: Mecânica,(2002) "4ª edição, Editora Edgard Blücher.

Romano, R. A. (2008) ."Karnopp Friction Model Identification for a Real Control Valve", 17th World Congress, Te International Federation of Automatic Control, Seul, Koreia.

Ramalho, F.;G.F.Nocilau,P.A. Toledo, "Os Fundamentos da Física", (1997) " 6ª eSão Paulo, Editora Moderna.

Serrano, M. M., Chang, A. H., Zhang, G., & Vela, P. A. (2015). "Incorporating frictional anisotropy in the design of a robotic snake through the exploitation of scales." Proceedings - IEEE International Conference on Robotics and Automation, 2015-June(June), 3729–3734.

Souza, N.C,A., Christina, L., Oliveira, B. De, Bevilaqua, D., Duarte, D. (2011). "Erekobot Alfa Project: Design and Construction of a Modular Robot Prototype", Brazilian Congress of Mechanical Engineering.

Transeth, A. A., Leine, R. I., Glocker, C., Pettersen, K. Y., & Liljebeck, P. (2008). "Snake robot obstacle- aided locomotion: Modeling, simulations, and experiments." IEEE Transactions on Robotics, 24(1), 88–104.

Zailmann, A. P., Gomes, S. S., & Soares, L. B. (2010). "Teoria E Experimentação No Estudo Sobre Atritos Em Atuadores Robóticos " Mecánica Computacional Vol XXIX, págs 2689-2708.

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