DESIGN, SIMULATION AND TESTING OF SHRIMP ROVER USING RECURDYN

Conference Paper · May 2013

3 authors:

Shivesh Kumar
Deutsches Forschungszentrum für Künstliche Intelligenz
12 PUBLICATIONS 24 CITATIONS

Mihir Bhagat
Delft University of Technology
4 PUBLICATIONS 5 CITATIONS

Gangadharan K V
National Institute of Technology Karnataka
86 PUBLICATIONS 321 CITATIONS

DESIGN, SIMULATION AND TESTING OF SHRIMP ROVER USING RECURDYN

Shivesh Kumar, Raghavendra S, Mihir Bhagat, K V Gangadharan
Department of Mechanical Engineering, National Institute of Technology Karnataka
P.O. Srinivasnagar, Surathkal, Karnataka-575025, INDIA
Email: shivesh.mecheng@gmail.com, raghav.s.777@gmail.com, mihir.r.bhagat@gmail.com, kvganga@gmail.com

ABSTRACT

The Shrimp rover is highly suitable for planetary exploration missions because of its unconventional wheel order, in-built passive adaptability and good ability to climb obstacles. It is a spatial multi-body system and a multi-variable, multi-parameter coupled non-linear system. Thus, kinematic and dynamic analyses for such systems are complex and time consuming. We propose the use of RecurDyn, a multi-body dynamics analysis software. Compared to other such softwares, it overcomes shortcomings like excessive simplification, low solving efficiency and bad solving stability. A potential application of this software in realistic modelling and dynamic simulation of the Shrimp rover is presented. Simulation results obtained from RecurDyn have been used to analyse the rover capabilities and select the actuators for the rover design. Simulation results are also validated experimentally. Thus, it is observed that an accurate and a reasonably fast simulation tool like RecurDyn has great potential in the field of space robotics.

1. INTRODUCTION

Robotic rovers uniquely benefit planetary exploration - they enable regional exploration with the precision of in-situ measurements, a combination impossible from an orbiting spacecraft or fixed lander [1]. In the last two decades, over 300 concepts have been generated and discussed [2]. Quite a few of these multi-functionality concepts have been designed and developed for the deployment of such solo rovers. Typically, most designs now are more or less identified, extensively analysed and in a few cases even validated.

Lately, there is a shifting trend which is characterized by an increased interest in developing rovers for long-term missions and for missions once a temporary base is set-up at say, Mars. For such missions, in comparison with a solo-mission rover, the environment remains the same, but the deliverables increase: long range capability, higher mobility, lower power consumption, ease of control. We examined and compared existing locomotion mechanisms using concept screening matrix and concept scoring matrix. It was identified that the Shrimp rover is the best option in terms of obstacle climbing capability, capacity to withstand topple, complexity of suspension, ease of control, size and power requirements.

Shrimp, designed by the Swiss Federal Institute of Technology - EPFL, is an innovative long-range rover architecture with 6 motorized wheels [3]. Using a rhombus configuration, the rover has a steering wheel in both, the front and the rear, and two wheels arranged on a bogie on each side. The front wheel has a spring suspension to guarantee optimal ground contact of all wheels at any time. The steering of the rover is realized by synchronizing the steering of the front and rear wheel and the speed difference of the bogie wheels. This allows for high precision manoeuvres and even turning on the spot with minimum slip.

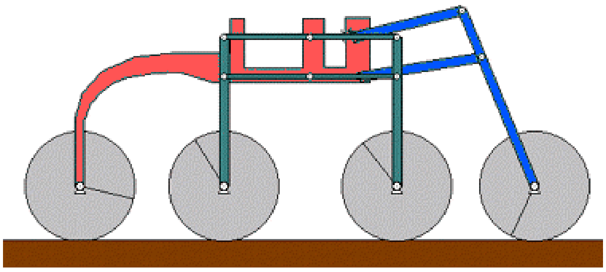


Figure 1: Shrimp rover schema from [3]

The use of parallel articulations for the front wheel and the bogies enables to set a virtual centre of rotation at the level of the wheel axis while maintaining a high ground clearance. This ensures maximum stability and climbing abilities even for relatively low friction coefficients between the wheel and the ground [4]. This rover is able to passively overcome unstructured obstacles of up to two times its wheel diameter. With this high mobility, this architecture is the perfect candidate for long range planetary missions.

Shrimp, with its unconventional wheel order, numerous linkages and in-built passive adaptability is quite a complex spatial multi-body system; it is also a multivariable, multi-parameter coupled non-linear system. The design process of Shrimp rover consists of determining crucial parameters like torque requirements of the actuators, amongst other things. Thus, the design of Shrimp involves the stipulation of dynamic behaviour of the system in certain terrains much before the rover is actually made. However, kinematic and dynamic analyses for such systems are complex and time-consuming. Also, it is difficult for beginners to learn and visualize how this system would perform under certain dynamic conditions.

RecurDyn, as a multi-body dynamics analysis software, can overcome some of the shortcomings of other traditional dynamics analysis software such as excessive simplification, low solving efficiency and bad solving stability. The solver of RecurDyn consists of equations of motion theory with recursive formulation, which make it fast and give the solution with high precision. Thus, the RecurDyn can aid in the design process of complex systems such as extra-terrestrial rovers.

The organization of the paper is as follows: Section 2 presents a potential application of RecurDyn in realistic modeling and dynamic simulation of the Shrimp rover. Section 3 discusses the manufacturing and assembly of the rover based on the actuator parameters obtained from the simulations performed. Section 4 explains the experimental setup developed to validate the results. Section 5 presents the results obtained and discusses the validation of simulation results. Finally, Section 6 concludes the work and discusses the limitations and further scope of development in this work.

2. SHRIMP: MODELING & DYNAMIC SIMULATION IN RECURDYN

Shrimp, initially conceptualized at the Autonomous Systems Laboratory at EPFL, has been designed and prototyped by several research institutions and companies. Our design of the Shrimp rover is based on the SHRIMP III rover research platform designed by Bluebotics [5].

2.1. Shrimp modeling

The solid modeling of the rover was done in CATIA V5. The CAD model of the full rover was imported into RecurDyn/Professional environment using STEP file format as shown in Fig. 2. The STEP file does not contain any information about the kinematic constraints present in the rover assembly. Hence, mechanical joints in the form of kinematic constraints were defined in RecurDyn/Professional environment. The details of all the joints present in the rover are presented in Tab. 1.

All the wheels were constrained to move with a constant angular velocity of π rad/s (30 rpm). Sliding joint friction (μ_{static}=0.5 and $\mu_{dynamic}$=0.3) was introduced at all the revolute joints for more realistic modeling.

Standard "Ground" body in RecurDyn was modified for the road/track definition. The road outline was made using the *outline* tool and the *outline surf* tool was used to make the road surface. The road was rendered as a surface on which the rover is expected to move. Structured terrains involving slopes, steps, concave & convex surfaces were modeled to evaluate the rover's performance. To make the contact of rover wheels with the road, surface to surface contacts were defined between the road surface and wheel surface. These surface contacts constrain the wheels to make a contact with road whenever possible. To make the tire to road contact more realistic, certain contact parameters such as spring coefficient = 1000 N.mm, damping coefficient = 1 and dynamic friction coefficient = 0.9 were set.

Table 1: Details of mechanical joints in Shrimp model in RecurDyn

Type of Joint	Number of Joints	Type of Actuation
Revolute Joint between body and wheels	6	Active
Revolute Joints in right parallel bogie	6	Passive
Revolute Joints in left parallel bogie	6	Passive
Revolute Joints in Front Fork	4+1	4 Passive, 1 Active (for front wheel steering)
Revolute Joints in Rear Fork	1	Active (for rear wheel steering)
Fixed Joints between different parts	31	No actuation

Shrimp rover uses a spring in the front fork to adapt to the terrain more effectively. The "spring force" feature of RecurDyn was used to install a spring in the front fork at the appropriate position. The spring properties such as stiffness and damping coefficient were initially chosen as 10 N.mm and 1 Ns/mm respectively.

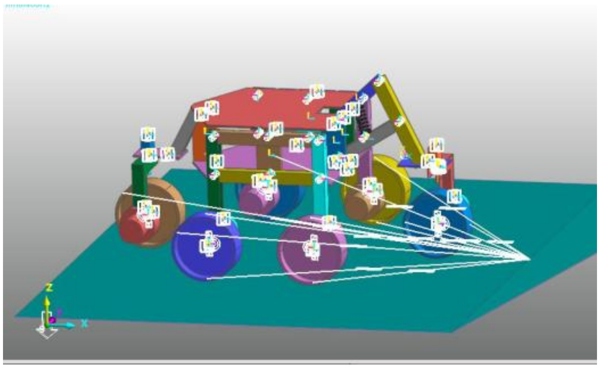


Figure 2: Shrimp Rover model in RecurDyn

Fig. 2 shows the completed model of Shrimp rover in RecurDyn/Professional environment.

2.2. Dynamic simulation

Kinematic and dynamic analyses (Dyn/Kin) for the rover were performed using the multi-body dynamics solver provided in RecurDyn. The solver uses fully recursive formulations which are highly efficient, stable and fast. Simulation times were suitably chosen for different simulations. The accuracy of the simulation could be varied easily by changing the number of time steps. Gravity (g=9806.5 mm/s2) was applied in –Y direction.

The rover' capabilities were tested on 3 distinct terrains:

1. Ability to adapt passively on concave / convex terrains

2. Ability to climb steps
3. Ability to climb an inclined surface

2.2.1 Curved surface adaptability

It is very important for the rover to adapt passively to concave and convex surfaces as the actual surfaces are not going to be flat in nature. For testing this ability, the rover was made to fall from a certain height on concave and convex surfaces. The behaviour of the bogie, when it comes in contact with the terrain, was observed. Fig. 3 shows the rover passively adapting to a concave terrain. It can be deduced that the parallel architecture of the bogies and the spring suspended fork provides a non-hyperstatic configuration allowing the bogie to adapt passively to any terrain profile.

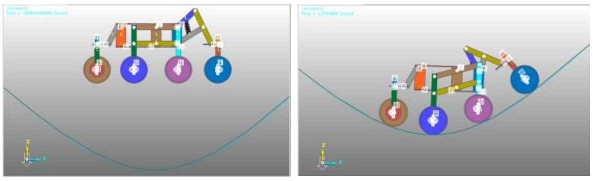


Figure 3: Concave terrain adaptability test

2.2.2 Ability to climb slopes

Shrimp can climb the terrains involving lateral or frontal inclination of up to 40° [3]. A terrain involving a frontal inclination of 40 degrees was designed in RecurDyn environment. Using Dyn/Kin, we were able to predict the driving torque requirements for each motor independently, while the rover traversed this sloping terrain. We had a simulation time of 22 seconds that was divided in 2200 time steps. Fig. 4 shows the rover climbing the terrain and the trace of its Centre of Gravity (CoG). Using RecurDyn's plot tool, we obtained the driving torque v/s time graphs. These, obviously, had some inherent noises affecting the actual data. Hence, a Fast Fourier Transform (FFT) was applied on all individual driving torque v/s time plots. The corresponding cut-off frequencies were also identified. The results were then filtered using a Butterworth filter of order 3 and the cut-off frequency as that was just identified. Fig. 5 (a) & 4 (b) show the driving torque v/s time variation of front and rear wheel respectively. From such driving torque v/s time plots, maximum torque requirements at each of the active joints can be predicted. This information can be used to aid in the selection of actuators, gear boxes, etc.

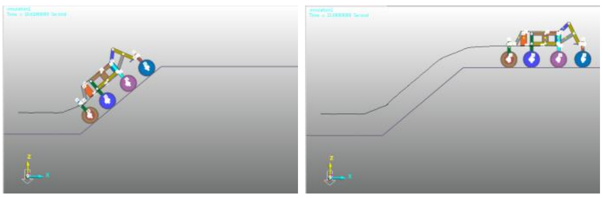
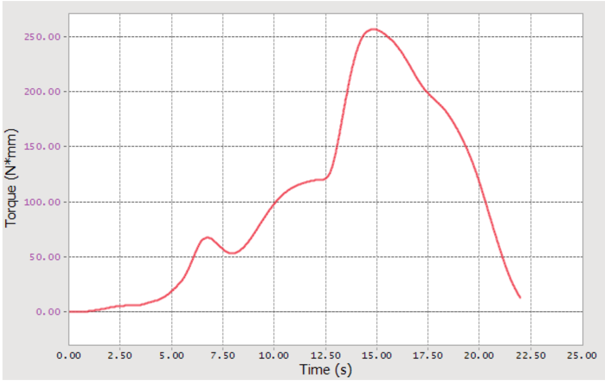
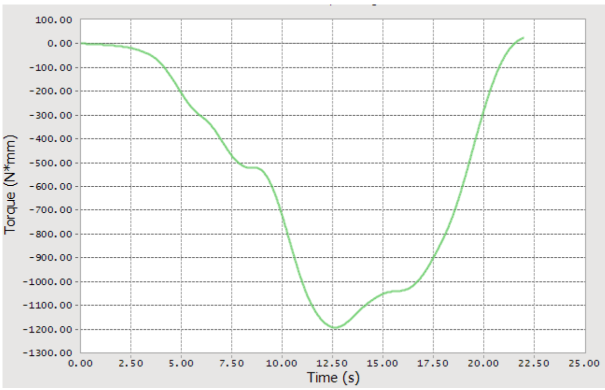


Figure 4: Shrimp rover climbing slope of 40 degrees



(a) Front wheel



(b) Rear wheel

Figure 5: Driving Torque v/s time characterstics

2.2.3 Ability to climb steps

Shrimp has the ability to climb steps of up to two times the wheel diameter [5]. A step of height 212 mm (wheel diameter being 106 mm) was modelled using the surface modelling tool in RecurDyn. Kinematic and dynamic analyses was performed for a simulation time of 16 seconds divided into 1600 time steps as the rover climbed the step. Fig. 6 shows the rover climbing the step. Similar to the previous case, noise reduction was performed on the solution using the inbuilt FFT and Butterworth filter tools in RecurDyn. Fig. 7 (a) & 7(b) shows the driving torque v/s time variation of front wheel and front wheel of the left parallel bogie respectively.

3. SHRIMP ROVER: MANUFACTURING

Knowledge of torque requirements, as obtained from section 2, helped us in selecting the motors for the rover. Tab. 2 shows the maximum torque requirements of each wheel as obtained from the simulations. We notice that the maximum torque required is 32.1 Kg-cm. Using a factor of safety (FOS) of 1.25, the torque requirement becomes 40.1 Kg.cm. The closest available off-the-shelf motor had a torque rating of 45.0 Kg.cm, thus, it made the most ideal choice.

The availability of components and facilities affected the design process greatly. Our final rover was manufactured with using as many off-the-shelf products as possible.

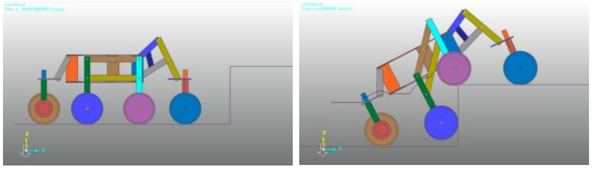
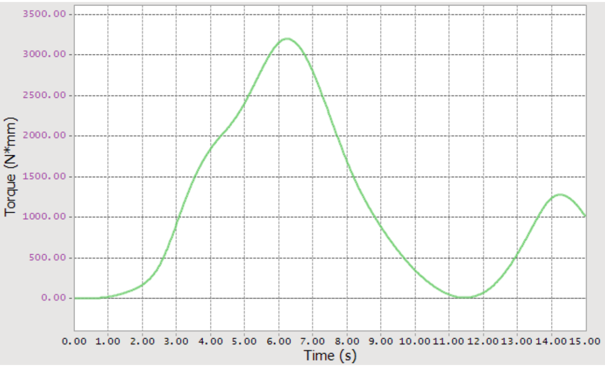
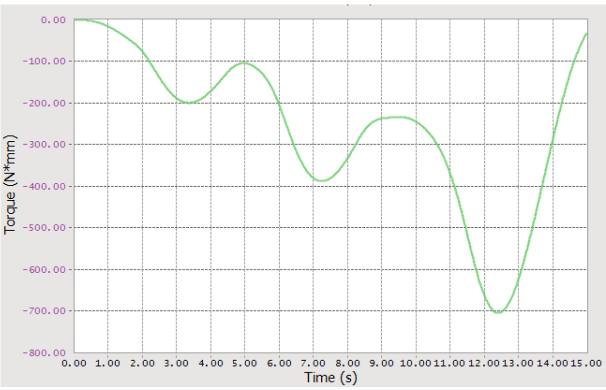


Figure 6: Rover climbing step of height 212 mm



(a) Front wheel



(b) Front wheel of the left bogie

Figure 7: Driving Torque v/s time characteristics while step climbing

3.1. Main body

We began the construction with a reasonably accurate (up to 0.5 mm accuracy) cut-out of 2mm thick aluminium plates, which form the top cover and the base plate of the rover. The shape of these twin plates is a square with a triangle appended on one of its sides. Thus, it's a pentagon, with the vertex of the triangle forming the rear of the rover. Fixed between the two plates, on either side, is an aluminium block, which has a pair of ball-bearings set into it. This block joins the two plates, serves as a column for load bearing and provides mounting points for the parallel bogies. The bearings on these blocks prove to be a revolute joint between the bogie and the main body. There are 2 other such blocks for mounting the front fork, while a plain, bearing-less block for supporting the rear fork.

Table 2: Maximum torque requirements at each wheel, as observed from simulations.

Wheel position	Torque (kg.cm)
Front	32.1
Right bogie (front)	7.5
Right bogie (rear)	7.4
Left bogie (front)	7.0
Left bogie (rear)	6.8
Rear	16.3

3.2. Parallel bogie

It consists of a set of links, which form a couple of two wheels, mounted on a support that can freely rotate around a central pivot. We used C-section links to build the frame of the bogies. The C-section allows for the frame to be sufficiently light without compromising on its strength and rigidity. We used two different cross-section sizes for the C-section links such that amongst the two, the smaller one could be perfectly inserted inside the bigger one. The frame was so formed that no adjacent links were of the same cross-section, thus, permitting us to create a freely rotating revolute joint by merely using a rivet. It is advised to exercise caution during the manufacture of the two bogies, because they need to be greatly identical. Any mismatch between the twins will give rise to non-uniform travel of rover.

3.3. Front and rear forks

The front fork consists of a 4 bar mechanism robustly mounted on 2 aluminium blocks. In all, 4 bearings are used to move the fork. The front fork has a servo mounted on it, to assist in the steering process. It does so by rotating the wheel about an axis passing through the wheel centre perpendicular to the ground.

The rear fork is a fixed link, at the end of which a wheel is mounted. It too, has a steering system to rotate the wheel.

3.4. Electronics sub-system

The electronics sub-system of the rover is distributed over the base station and on-board. On-board control system includes two Atmega16 based development boards interfaced in Master-Slave configuration (SPI Interface) [6], which controls various sensors and actuators installed on the rover for its operation. The sensor data and control signals are wirelessly transmitted to the base station using a pair of Xbee trans-receiver modules. The base station involves a PC running on Intel Core 2 Duo processor, which provides a MATLAB based GUI to the end-user to interact with the rover. A wireless camera has also been installed on board which uses a separate RF channel and sends the live video feed to the GUI. Fig. 8 shows the overall schematic of the control system of the rover. Whereas, Fig. 9 shows the completed rover.

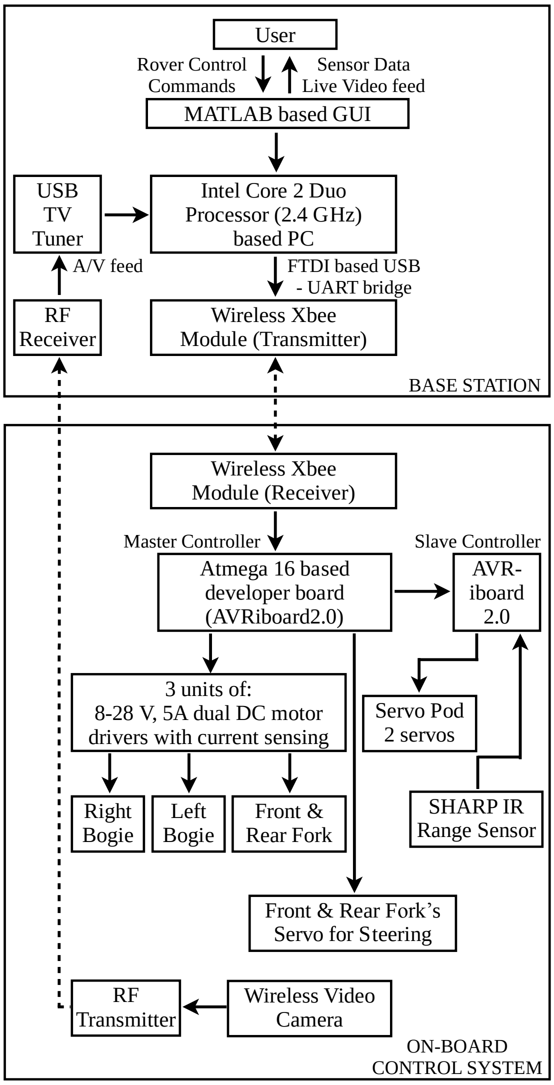


Figure 8: Schematic of control system of rover.

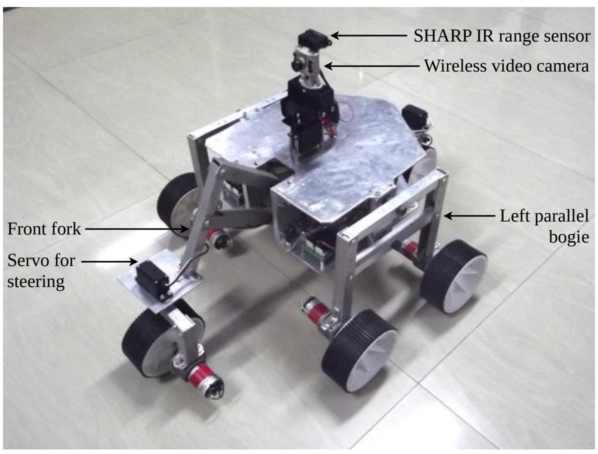


Figure 9: Completed Rover

4. EXPERIMENTAL SETUP

The rover was tested to experimentally validate the results of RecurDyn. The objective was to compare RecurDyn results against experimental results with respect to the torque requirements of each individual motor. The rover was made to traverse on two types of terrains, one including an inclined surface and the other having a step. As observed in section 2, using RecurDyn, the driving torque requirements of each wheel were directly available as time graphs, for both these terrains. However, for obtaining experimental results, we measured the armature current variation at each motor while the rover fared through these obstacles. These readings were later multiplied by K_t (the motor torque constant) to obtain the corresponding torque values. A separate experiment was conducted to measure the value of K_t.

$$\tau = K_t \times I \qquad (1)$$

where, τ is the torque, N.m
I is the current, A.

Fig. 10 shows the basic experimental setup and better explains the method of obtaining data for real-time driving torque measurement.

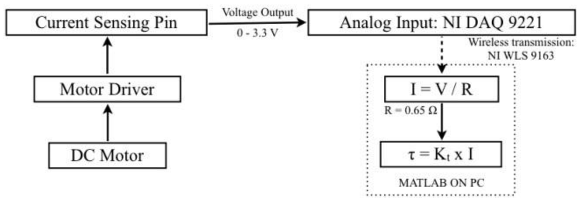


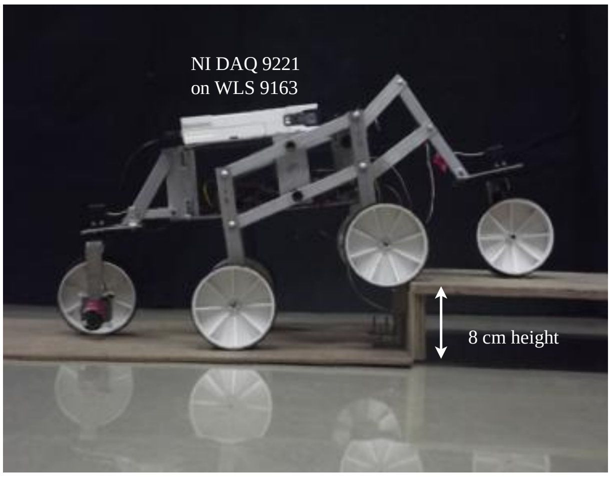
Figure 10: Schematic for real-time driving torque measurement

4.1. Step test

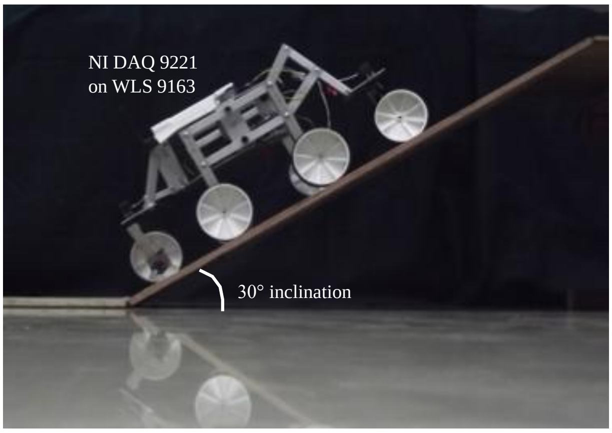
This test consisted of putting a step in the path of the rover. The step size was arbitrarily chosen as 8 cm high. The setup comprised of a base, a step and a raised platform, all of which were made of plywood. This ensured that the coefficient of friction between the wheel and surface remained constant. The rover had no difficulty in climbing the step and we were successfully able to measure the current variation at all motors independently as the rover traversed the path. Care was taken to ensure that the experimental setup matched the setup used for simulations in RecurDyn. Fig. 11(a) shows the rover during step test.

4.2. Inclined slope test

An inclined surface, big enough to accommodate the rover completely on it, was used as the next obstacle. The inclination was arbitrarily chosen as 30 degrees. This setup also consisted of a base and a raised platform. We performed the experiment in a similar manner to obtain real-time driving torque values. The experimental setup was made to match the setup used for simulation in RecurDyn. Fig. 11(b) shows the rover during slope test.



(a) Step test; 8 cm height.



(b) Slope test; 30 degree inclination.

Figure 11: Rover traversing terrains for experimental validation

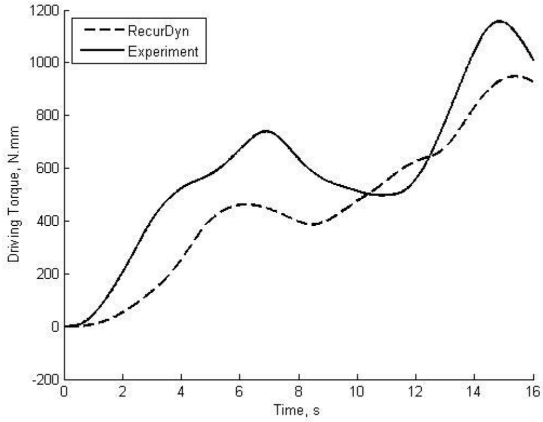
5. RESULTS & DISCUSSIONS

The driving torque data obtained from the experiments was imported into MATLAB. The noise was filtered away using FFT and Butterworth filter. RecurDyn simulation results were also exported in text file format and were subsequently imported into MATLAB to perform a comparative study on the driving torque v/s time plots obtained from experiments and RecurDyn. A common sampling frequency of 100 Hz was used in both real and virtual environments. The simulation time in inclined slope test was 22 seconds and 16 seconds in step test. Fig. 12 (a) shows the driving torque v/s time plot of back wheel in the slope experiment and Fig. 12 (b) shows the driving torque v/s time variation of front wheel in the step experiment.

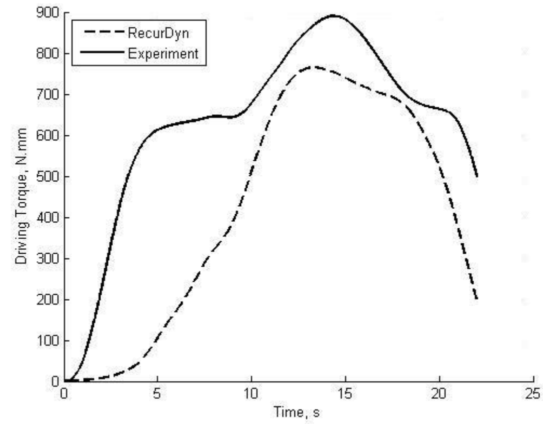
The mean absolute percentage error (MAPE) is calculated with the help of Eq. 2.

$$MAPE = \frac{1}{n}\sum_{1}^{n}\frac{|\tau_{exp}-\tau_{sim}|}{\tau_{exp}} \quad (2)$$

MAPE for rear wheel (in slope test) was found to be 42.87%. MAPE for front wheel (in step test) was found to be 35.62%. Similar comparisons can be performed for each motor in both the cases easily. To avoid redundancy, in this paper, we present the comparisons only for the above two cases. It was found that MAPE value typically varies between 35 to 45 % for different cases.



(a) Slope test; rear wheel; 30 degrees inclination.



(b) Step test; front wheel; 8 cm height.

Figure 12: Driving torque v/s time plots comparison between real and simulated data

The primary reason for having such large variations in results is that the electrical DC drive motor is not included in the RecurDyn simulation. The DC motor adds various non-linearities to the system such as BEMF voltage, friction at motor bearings, etc. which haven't been accounted for. Other reasons contributing to the error could be the incorrect modelling of joint friction at each revolute joint; incorrect estimate of contact friction between the road and wheel surface; mismatch between modelled and actual mass-inertia properties of different parts in the assembly. Also, nuts, bolts, clamps, bearings and other such parts were not included in the RecurDyn model. This simplification might have contributed to the error as well. If these sources of error can be suitably accounted for, a better comparison can be drawn.

However, the software was found to be particularly useful for selection of actuators required by the rover for particular payload capabilities. It shows potential of being able to greatly assist in the design process.

6. CONCLUSION

We presented the modelling and dynamic simulation of a long-range planetary exploration rover using RecurDyn. Its solver and in-built tools show the potential of greatly aiding the design process in space robotics. The shrimp rover's actuator selection would have been significantly more difficult or long-winded, if other means were utilised. The maximum driving torque requirement was easily and accurately identified using RecurDyn. Tests to check the capabilities of shrimp rover showed a significant mismatch between real-time data and simulated data. However, this can primarily be attributed to insufficient modelling data and possible discrepancies in manufacturing of the rover.

As an end-user, we are satisfied with the capabilities and ease of use of RecurDyn. Future scope includes more accurate validation by eliminating known sources of error. This is also subject to availability of resources and facilities to carry out substantial work.

7. REFERENCES

1. Tompkins, P. (2005). *Mission-directed path planning for planetary rover exploration*. MA thesis, The Robotics Institute, Carnegie Mellon University

2. McTamaney, L.S., Douglas, B.D. & Harmon, S.Y. (1989). Mars Rover concept development. Proc. SPIE Conf. 1007, Mobile Robots III.

3. Estier, T., Piguet, R., Eichhorn, R. & Siegwart, R. (2000). Shrimp, a rover architecture for Long Range Martian Mission. In Proc. 6th. ESA workshop on Advanced Space Technologies for Robotics and Automation, The Netherlands.

4. Estier, T., Crausaz, Y., Merminod, B., Lauria, M., Piguet, R., R. Siegwart. (2000). An innovative Space Rover with Extend Climbing Abilities. In Proc. of Space and Robotics, Albuquerque, USA.

5. Shrimp III by BlueBotics. Online at *http://www.bluebotics.com/media/Flyer_ShrimpIII.pdf?462722*, October 2012

6. ATmega16 (AVR microcontroller) datasheet. Online at http://www.atmel.com/Images/doc2466.pdf, December 2012.