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ANTARCTICA ROVER DESIGN AND OPTIMIZATION FOR LIMITED POWER CONSUMPTION

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Abstract: The design process of the new locomotion platform called K11 aims at obtaining a rover capable of traveling thousands of kilometers at 1 m/s in the harsh environment of Antarctica during summer and carrying a 100 kg payload. A model including the drive-train power consumption and masses is used to optimize the parameters of the rover in order to minimize the power consumption. The obtained configuration consumes theoretically only 58W on flat ground and has limited power consumption while climbing a slope. The prototype built based on the optimization results is used to confirm the model.

Keywords: Rover, Antarctica, Locomotion, Power consumption, Optimization, Modelling

1. INTRODUCTION

The purpose of this project is to design a locomotion platform capable of traveling thousands of kilometers at 1 m/s in Antarctica during summer and carrying a 100 kg payload. The power consumption has to be kept lower than 300 W. This rover will be used by the NASA Ames Research Center as part of the Life on Ice, Robotic Antarctic Explorer project (LORAX). One of the objectives is to collect and analyze ice cores and build up a geographic map of distribution of microorganisms in Antarctica. This locomotion platform (K11) will also be used for a trans-Antarctic traverse during the International Polar Year in 2007/8.

Within the design of a robotic platform, there exists a tradeoff between mass, wheel size, motor type, gearhead ratio and all-terrain capabilities. In order to find the best suitable parameters, an optimization process is implemented. It minimizes the power consumption using models of the drive-train power consumption, wheel-soil interaction and masses.

The model is described in section 2 and the optimization process in section 3. The prototype built to confirm the model is then described in section 4.

1.1 Related work

The Nomad rover from Carnegie Mellon University (CMU) (Wettergreen *et al.*, 1999) was previously used by the NASA ames research center for navigational autonomy development and testing, and for analysis of wind and solar power for exploration of Antarctica (Moorehead *et al.*, 1999).

Fig. 1. Sastrugis in Antarctica

They also used it for robotic search for Antarctica meteorites (Apostolopoulos *et al.*, 1999; Pedersen *et al.*, 2005). Nomad is a proven platform, however it was designed for being used in the Atacama Desert, therefore it is too large to be easily deployed in Antarctica and consumes too much power to travel more than 100 km in a field season (1-2 months) using solar and wind power.

An exploration robot for Antarctica was also built by the Dartmouth College (Gravenkötter and Hamann, 2004).

A practical approach to rationalizing configuration design of robotic locomotion through quantitative studies was developed at CMU (Apostolopoulos, 2001). This study provides a computational framework for analyzing a rover design with some indices of performance: trafficability, maneuverability and terrainability. Another study developing tools for rover chassis and performance evaluation can be found in (Richter *et al.*, 2004).

1.2 Environment

Antarctica is the coldest place on earth, there is very little precipitations making it a desert. The maximal stable wind speed during summer in Antarctica is 20 m/s while the minimal temperature is -40°C. However, the rover must be usable during summer in California (+40°C).

The soil consists of ice covered by a compact layer of snow. The soil parameters aren't known very precisely and can vary from loose to packed snow very similar to ice. The wind causes the surfacing snow to move, creating fields of snow mounds called sastrugi (see Figure 1) with the same principle as sand dunes.

To explore Antarctica the rover has to be able to pass over sastrugi 0.5 m high and to travel on ice as well as packed and loose snow.

2. MODELING

The model includes approximation of masses, motion resistance and power loss inside the motors, gearheads and amplifiers.

The power consumption (Pel) is computed as the mechanical power divided by the efficiency (Equation 1):

$$P_{el} = \frac{\Omega_w \cdot T_w}{\eta_{ampli} \cdot \eta_{mot} \cdot \eta_{gear}} \tag{1}$$

$$T_w = R_{tot} \cdot \frac{d_w}{2} \tag{2}$$

$$\Omega_w = \frac{V_{rover}}{d_w/2} \tag{3}$$

where Ω_w and T_w are the wheel speed and torque, d_w denotes the wheel diameter while V_{rover} is the forward speed of the rover. The amplifier efficiency (η_{ampli}) is considered to be constant while the motor and gearhead efficiencies (η_{mot} and η_{gear}) are functions of differents parameters. The motor efficiency is a function of speed, torque and motor type and the gearhead efficiency is a function of gearhead ratio, applied torque and maximal sustainable torque.

In Equation 2, the total motion resistance (R_{tot}) is used to compute the required wheel torque. It consists of rolling and compaction resistance (R_r and R_c), gravitational (R_g) and wind (R_{wind}):

$$R_{tot} = R_c + R_r + R_g + R_{wind} \tag{4}$$

The compaction resistance is due to soil compaction (sinkage) (Wong, 2001) and depend on soil parameters (n,k_Φ, k_c):

$$R_c = \frac{\left(\frac{3 \cdot F_N}{\sqrt{d_w}}\right)^{\frac{2n+2}{2n+1}}}{(3-n)^{\frac{2n+2}{2n+1}}(n+1)(k_c + b_w \cdot k_\Phi)^{\frac{1}{2n+1}}} \tag{5}$$

where F_N stands for the normal force applied on the wheel and b_w is the wheel width.

The rolling resistance (Equation 6) includes slipping, scrubbing, deflection of tire and tread elements. Here, the factor ξ is considered similar to Nomad's and constant. The gravitational resistance is the projection of the weight on the slope (Equation 7). The wind resistance (Equation 8) is computed for a laminar flux and with constant parameters.

$$R_r = F_N \cdot \xi = \frac{M_{tot}}{N_w} \cdot cos(\theta) \cdot \xi \tag{6}$$

$$R_g = F_T = \frac{M_{tot}}{N_w} \cdot sin(\theta) \tag{7}$$

$$R_{wind} = C_x \cdot \rho \cdot S \cdot \frac{V_{wind}^2}{2} \tag{8}$$

where N_w denotes the number of wheels, F_T the tangent force applied on the wheel, C_x the form coefficient of the rover, S the perpendicular surface to the wind and V_{wind} the relative speed of the wind.

The total mass of the rover M_{tot} (Equation 9) is computed as the sum of each component's mass. The model of each component's mass is obtained by fitting real values of different manufacturers.

$$M_{tot} = f(d_w, b_w, T_{MaxMot}, r) \tag{9}$$

where T_{MaxMot} is the maximal motor torque and r is the gearhead ratio. Remark that the mass is a function of the optimization parameters (see Section 3.1).

3. OPTIMIZATION

The optimization process makes use of the MATLAB Optimization Toolbox. It tries to minimize the total electrical power required to drive the rover on flat ground at a forward speed of 1 m/s (Equation 1 with $V_{rover} = 1$ and $\theta = 0$) while satisfying specific constraint equations .

3.1 Parameters

The four parameters of the optimization process are the wheel width (b_w) and diameter (d_w), the maximal motor torque (T_{MaxMot}) and the gearhead ratio (r):

$$\overrightarrow{x} = (d_w, b_w, T_{MaxMot}, r)^T \tag{10}$$

3.2 Constraint equations

The main constraints (Equations 11 to 17) express the capability of the rover to respect a maximal ground pressure (keeping snow sinkage low), to climb a maximal slope of 10°, to pass over an obstacle of 0.5 m high and the capability of the motor and gearhead to sustain the required torque and speed.

$$GP = f(\overrightarrow{x}) \leq GP_{max} = 10\ [kPa] \tag{11}$$

where GP denotes the ground pressure.

$$P_{MaxMot}(\overrightarrow{x}) \leq P_{el}(\overrightarrow{x}) \quad , \ \theta = 10° \tag{12}$$
$$T_{MaxMot}(\overrightarrow{x}) \leq T_{mot}(\overrightarrow{x}) \ , \ \theta = 10° \tag{13}$$
$$T_{MaxGear}(\overrightarrow{x}) \leq T_w(\overrightarrow{x}) \quad , \ \theta = 10° \tag{14}$$
$$T_{MaxInterMot}(\overrightarrow{x}) \leq T_{mot}(\overrightarrow{x}) \ , obstacle \tag{15}$$
$$T_{MaxInterGear}(\overrightarrow{x}) \leq T_w(\overrightarrow{x}) \quad , obstacle \tag{16}$$
$$\Omega_{MaxMot}(\overrightarrow{x}) \leq \Omega_{mot}(\overrightarrow{x}) \tag{17}$$

where the left hand side of the equations denotes the maximal capacity of the components while the right hand side denotes the obtained values of the algorithm.

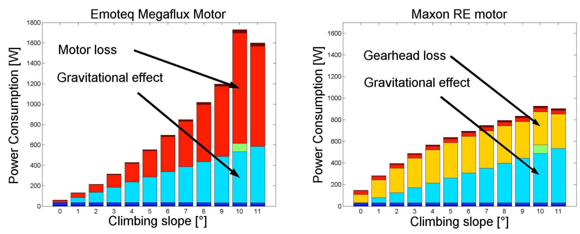

Fig. 2. Sensitivity of power consumption on climbing slope. Left: the power consumption for a high torque motor explode. Right: the sensitivity is smaller for a less torque capable motor

Climbing an obstacle is considered as an intermittent working ($T_{MaxInterMot}$, $T_{MaxInterGear}$). These obstacle constraint equations (15 and 16) are computed with a slope of $\theta = 45°$ and a wheel load repartition computed separately.

The constraint equations also include other constraints such as the maximal reasonable wheel diameter and the maximal gearhead ratio, but they are not given in detail here.

3.3 Results

The optimization results give a minimal power consumption of about 58 W for a big wheel diameter, a high torque motor type and a gearhead ratio equal to 1 (Table 1, configuration 1). However, the power consumption increases dramatically with variations of the slope for such a configuration (high sensitivity). Then, there exists a tradeoff between this sensitivity and the power consumption on flat ground (see Figure 2).

To keep the power consumption sufficiently low on an inclined slope, the chosen motor type must have a lower maximal sustainable torque and the required gearhead ratio is higher (Table 1, configuration 2). Then the power consumption increases to 100W on flat ground.

The power consumptions computed with the model for these two configurations can be found in Table 2.

Table 1. Optimization results

Parameter	Config 1	Config 2
d_w	0.8 m	0.8 m
b_w	0.21 m	0.19 m
T_{MaxMot}	61.7 Nm	0.36 Nm
r	1.0	416

Table 2. Power consumption

Total $P_{el} [W]$ config 1	config 2	Slope θ [°]	V_{rover} [m/s]	V_{wind} [m/s]
58	101	0	1	0
1226	206	10	0.3	20
1731	715	10	1	20

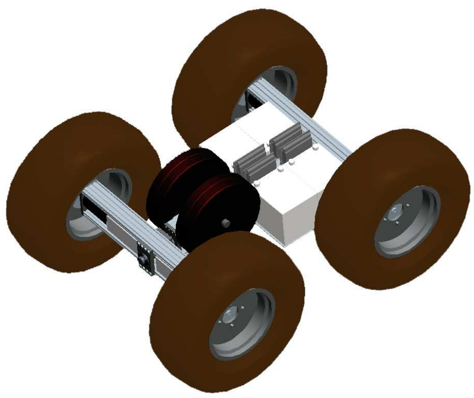

Fig. 3. The K11 rover prototype

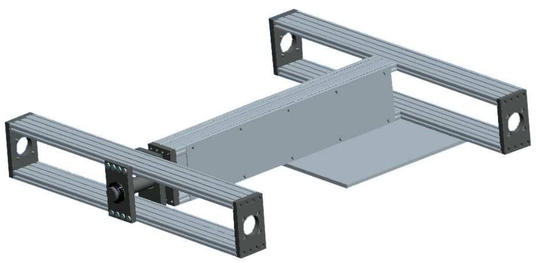

Fig. 4. Chassis design of the K11 locomotion platform prototype

4. THE K11 PROTOTYPE

The prototype is used to confirm the model and the optimization results. The payload is replaced by weight plates made of cast iron (see Figure 3).

The rover is driven by four 250 W DC motors with graphite brushes mounted with planetary gearheads ($r = 308$) and encoders, all from Maxon Motor SA. The wheels are ATV tires from ITP with aluminium rims, with a diameter of 0.63 m for 0.27 m width. The power supply consists of four 12 V lead batteries from VARTA in series.

The total mass of the prototype without payload is 160 kg.

4.1 Mechanical design

The chassis was designed by BlueBotics SA. It consists of a simple H structure and a joint around the roll axis to ensure the wheels' contact with the ground (Figure 4).

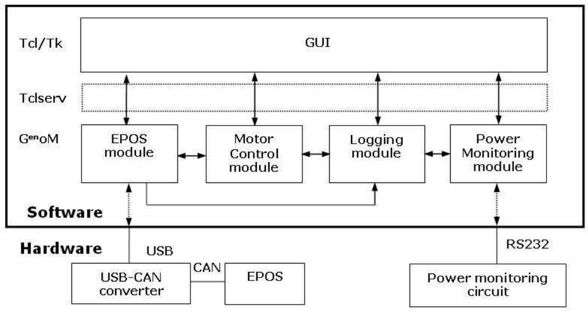

Fig. 5. Four G^{en}oM modules are used to control and monitor the rover. The arrows represent the information flux.

4.2 Electronics and control

A G^{en}oM environment (Fleury *et al.*, 1997) is used to control and monitor the rover from a computer with a graphical user interface (GUI). The architecture is visible in Figure 5.

The motors are driven by four positioning controllers (EPOS) from Maxon Motor SA providing a speed control. They are connected to the computer with a CAN bus and also provide informations about the currents, positions and speeds.

An electronic circuit is used to measure the power consumption of each motor. It uses four current-sense amplifiers from Maxim (MAX4080S) and a microcontroller from Microchip (PIC16f876) that sends the measured values to the computer with a serial bus.

The motor controller uses a principle developed for the FIDO rover of the NASA/Jet Propulsion Laboratory (Baumgartner *et al.*, 2001). It uses a velocity synchronization algorithm to avoid the wheels fighting one another.

The computer uses four G^{en}oM modules which make the communication with the EPOS and the measuring circuit, log the data and compute the motor controller algorithm.

5. RESULTS

The prototype was built and is currently being tested on snow [1].

6. CONCLUSION

Using models of the drive-train power loss, wheel-soil interaction and masses, the optimization pro-

[1] note: this work is part of a master project ending at the end of February, this is why the results and conclusion are very short. The tests of the prototype will be presented in the final paper.

cess provides a rover configuration with limited power consumption.

The theoretical power consumption of the rover on flat ground is three time less than required, however it increases quickly with increasing slope and the rover must go slower while climbing slopes.

More testing will be done with the prototype for being include in this paper (see note 1).

7. ACKNOWLEDGMENTS

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