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Modeling and design of geared DC motors for energy efficiency: Comparison between theory and experiments

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ABSTRACT

Energy efficiency is a growing concern in today's mechatronic designs. In recent years, many works have emerged presenting energy-efficient actuators with electrical motors. However, there is little consistency in the way energy consumption is calculated. Drive inertia, motor efficiency and controller efficiency are often neglected in optimizations, and so are the load- and speed-dependency of the losses and other non-linearities. While this approach works well in stationary circumstances, it can lead to significant errors in highly dynamic tasks with a wide range of operation, such as the ones faced by actuators in the field of robotics. This paper discusses the losses occurring in an actuator consisting of a DC motor and gearbox as it is forcing a swinging motion on a pendulum. From this simple case study, some general recommendations on the modeling of energy losses are formulated. Combining data from manufacturer's datasheets with empirical data, the approach presented in this paper was able to predict the energy consumption for this specific case with an error of less than 10%.

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1. Introduction

As the field of mobile robotics is growing, so is the demand for lightweight and energy-efficient actuators. Energy efficiency is important because it allows for a longer autonomy of the robot and reduced weight of the battery pack, again decreasing energy demand and possibly increasing dexterity. Many designs feature DC motors, which, on top of their easy implementation and flexibility, offer the advantage of having high maximum efficiency values. However, unlike most other industrial applications in which motors are working close to their rated point of operation, robots typically require the motor to be operated at a variable speed and load. In the latter case, additional inertial loads have to be overcome, and the motor will no longer be able to operate at its maximum efficiency. Moreover, in lightweight applications, motors are often pushed to their torque limits, operating far away from their most efficient region.

In the past years, many papers have appeared in which actuators for mobile applications are optimized for energy efficiency. Very often, calculations are based entirely on the energy consumption at the output shaft of the motor [1–8], which implies that the motor efficiency's dependency on torque and speed and its inertia are neglected. Some authors also consider electrical power consumption by introducing a DC motor efficiency model. Typically, the model includes resistive losses [9,10] and sometimes losses proportional to motor speed [11,12]. In those papers which utilize a DC motor model, inertia of the motor is usually included, but gearbox inertia is rarely taken into account [9]. In many actuator systems, however, the reflected inertia of the motor and gearbox is much larger than the link inertia [13], which implies that generally these inertias cannot be neglected. This is recognized in Roos et al. [14], where the authors present a motor-gearbox selection method that includes inertias and a DC motor model. Other evidence of the importance of DC motor models can be found in Brown and Ulsoy [12]. In an optimization on a robot arm, the authors claim that 2/3 of the energy savings they accomplished could be attributed to a more efficient use of the motor.

The aim of this paper is to study how the load- and speed-dependency of motor efficiency affects the overall efficiency of the actuator, and to see whether it is possible to model these losses with reasonable accuracy by using a complex nonlinear model based only on datasheet information. First we will discuss motor, gearbox and controller efficiency and present the models that will be used to describe them (section 2): a nonlinear model of gearbox and controller losses depending on the direction of power flow, and a DC motor model. In this section, we will also briefly address different methods of calculating the energy

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consumption from the motor power. Next, we establish the equations that describe an actuator driving a pendulum (Section 3), the set-up which we will use to test our methods. In Section 4, we present simulations of the actuated pendulum and study its energy consumption. To evaluate to what extent the actuator model is able to capture the occurring losses, experiments on a physical pendulum set-up are compared to the simulated results (Section 5), and empirical adjustments are suggested to improve the model. Finally, the simulation and test results are synthesized to produce general recommendations for the calculation of energy efficiency in variable load and speed applications (Section 6).

2. Load- and speed-dependent efficiency of gearbox, motor and drive circuitry

2.1. Gearbox efficiency

Even though direct-drive solutions exist and are being offered by robot manufacturers, most actuator designs use gearing in order to match the output load and speed to the motor's most efficient operating range. Gears, however, introduce energy losses. Several models have been developed to predict the efficiency of a specific type of gear pair (spur gears, bevel gears, ...), usually focusing on a specific type of loss. Typically, gear losses are separated into load-dependent and load-independent losses. An extensive review of load-independent loss models is given in Stavytskyy et al. [15]. Many models for predicting load-dependent losses exist, and development of such models has not stopped in recent years [16–19]. Much work on gear efficiency has been performed in the 1980s by Anderson and Loewenthal. Fig. 1 presents a typical efficiency plot for a spur gear pair, based on their commonly used model published in 1980 [20]. A strong dependency on torque exists, whereas the dependency on speed is less pronounced. At low torques, efficiency decreases quickly. Regarding speed, low speeds yield higher efficiencies.

In robotics, the reduction ratios offered by spur gears alone are usually insufficient. Planetary gearboxes are a popular solution because of their ability to achieve large reduction ratios at relatively small size. Their complexity, however, makes it difficult to obtain decent efficiency models. An overview of the most widely known efficiency formulas for planetary gearboxes is given in Pennestri and Valentini [21]. Generally, these formulas only include meshing losses, meaning that inertia effects and speed-dependent losses are neglected. More detailed models such as Pelchen et al. [22] include these losses, but when compared to tests, do not always provide a good estimate of the gearbox efficiency. Furthermore, all of these models require some knowledge of gear design (i.e. module/pitch diameter, number of teeth, etc.) and are therefore of little practical use when choosing a gearbox from a catalog. For these reasons, we will stick with the constant efficiency value specified in the catalog for the calculations made in this paper.

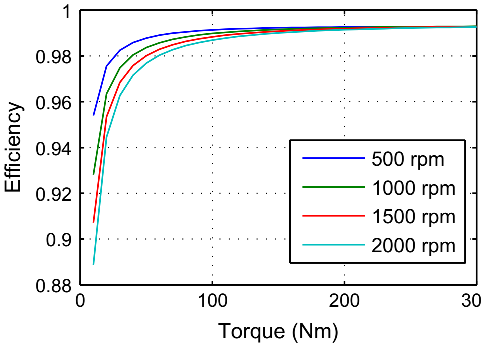

Fig. 1. Efficiency plot for the gear pair specified in Table 1, based on the model of Anderson and Loewenthal [20]. Gear efficiency decreases quickly at low torques, especially at high speeds.

Table 1
Properties of the gear pair presented in Fig. 1.

Teeth on pinion	48
Teeth on gear	80
Diametral pitch	8 mm
Face width	10 mm

We will, however, take the dependency on power flow into account. As suggested in Giberti et al. [23], we can write the relationship between load torque T_l and motor shaft torque T_{shaft} by defining an efficiency function C:

$$T_{shaft} = C \cdot T_l \tag{1}$$

$$C = \begin{cases} 1/\eta_{tr} & \text{(load driven by motor)} \\ \eta_{tr} & \text{(motor driven by load)} \end{cases} \tag{2}$$

in which η_{tr} is the gearbox efficiency. Depending on whether power is flowing from the motor to the load or vice versa, the gearbox losses will lead to an increase or decrease of the motor torque. Consequently, whether the efficiency value has to be put in the numerator or denominator of Eq. (1) depends on the state of the system. This is accounted for by the definition of the efficiency function C (Eq. (2)). A more detailed discussion can be found in the test section (Section 5.2.1), where the effects of this phenomenon on motor current are discussed.

On a final note, just like ordinary gear pairs, planetary gearboxes suffer a sharp decrease in efficiency when used at low torques. Another important characteristic is the number of stages; by adding stages to a gearbox to increase the gear ratio, the gearbox's efficiency is reduced due to the increased number of components and the losses associated with them. For this reason, gearbox efficiency will tend to be lower for high gear ratios.

2.2. Motor efficiency

In mobile robotics, where portability and weight are important issues, a DC power source such as a battery pack is usually the most convenient solution. Consequently, a DC motor is the most likely candidate when choosing a motor type. DC motor datasheets generally specify a maximum efficiency. However, when a motor is operated at variable load and/or varying speed, its efficiency can drop far below this value [24]. To optimize the energy efficiency of such applications, a motor efficiency model is required. The motor's electrical power consumption is calculated with the following DC motor model [25]:

$$\begin{cases} I = \frac{T_m + \nu_m \dot{\theta}_m}{k_t} \\ U = L\frac{dI}{dt} + RI + k_b \dot{\theta}_m \end{cases} \tag{3}$$

which gives the relationship between motor torque T_m and motor speed $\dot{\theta}_m$ and current I and voltage U. The model includes damping losses $\nu_m \dot{\theta}_m$, a supplementary torque proportional to the motor's speed $\dot{\theta}_m$ to account for friction between the motor's components, and resistive losses RI, which take up a part of the motor voltage and are proportional to the torque delivered by the motor. Furthermore, there is a voltage loss $L\frac{dI}{dt}$ due to terminal inductance. The inductance L is however three to four orders of magnitude smaller than the resistance R and the speed constant k_b, and can therefore be neglected if the torque does not contain any

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