Falcon Motors Specifications

G. Aiello and G. Rauter*

Bio Inspired RObotics in Medicine Lab, *University of Basel, Basel*

December 2016

E-mail: gregorio.aiello@unibas.ch

Abstract

In this report are shown the characteristics of the motors inside the Falcon controller by Novint, after analyzing their specifications and details we will try to improve the communication performance of the robot changing motors and using EtherCAT data transmission. The last section will cover the basic theoretical background of electric drives theory, necessary to choose the motors of my telemanipulator.

Introduction

The RS-555PH from Mabuchi Motor is a well-built DC motor. Can also be used for many hobbyist projects such as radio controlled vehicles, robotics, model-building, home automation, and more! The 5-pole construction utilizes permanent magnets, so the motor produces high torque with high efficiency. Mounting is simplified by three 3 mm mounting holes on the face of the motor. Specifications:

- Speed (without load): 5560 rpm
- Speed / Torque: 3950 rpm / 380.3 gcm
- Stall torque: 1360 gcm

- Current draw (at 5000 rpm): 1.25A
- Nominal voltage: 12 VDC
- Operating voltage: 7 to 12 VDC
- Weight: 220 gm (7.6 oz)
- Shaft diameter: 3.0 mm (1/8")
- Shaft length: 10.5 mm (1/2")
- Dimensions: 37.5 mm x 57 mm (1 1/2" x 2")

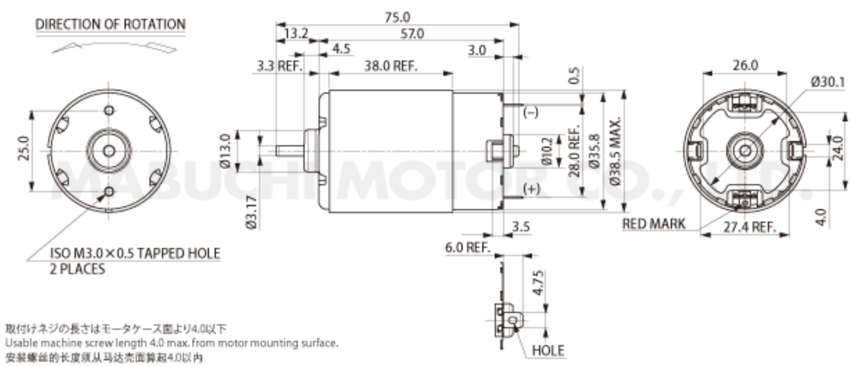

Figure 1: Schematic of the motors used in the Falcon controller by Novint.

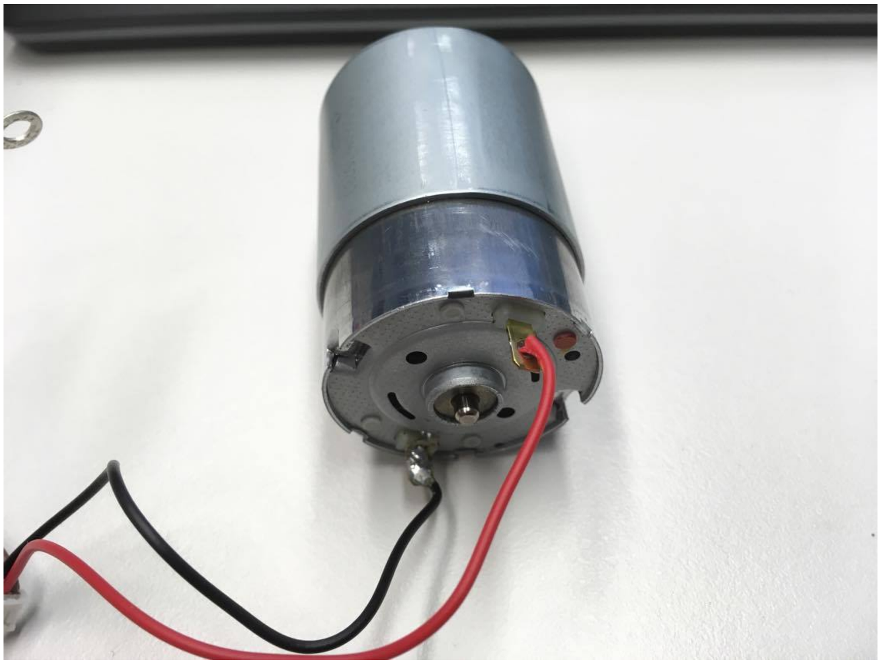

Figure 2: Rear view of the motors used in the Falcon controller by Novint.

Figure 3: Frontal view of the motors used in the Falcon controller by Novint.

Figure 4: Side view of the motors used in the Falcon controller by Novint.

Electric Machines Theory

Before addressing the study of electrical machines it is convenient to introduce the study of the basic principles of electromechanical energy conversion. The starting point for understanding this theory is the primitive machine in Fig. 5:

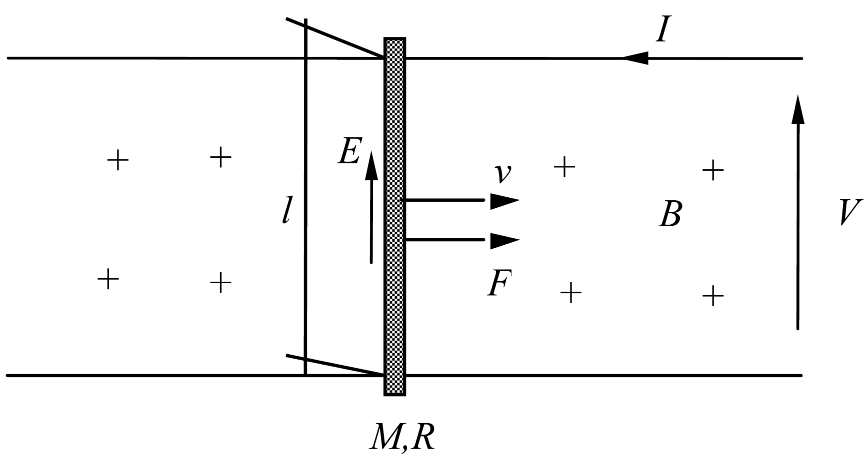

Figure 5: The primitive machine, useful to introduce the rules of electric motors.

It is a device consisting of:

- a straight conductor of length "l", mass "M" and resistance "R" free to move in horizontal direction

- a uniform magnetic field B perpendicular to the conductor rails plane (in Fig. 5 it is directed into the page). It follows that, if the conductor moves at a linear speed "v", an electromotive force is induced across an element "dl" of the conductor

It follows that, if the conductor moves at a linear speed "v", an electromotive force (EMF) is induced across an element "dl" of the conductor:

$$dE = (\vec{v} \times \vec{B}) \cdot \vec{dl} \tag{1}$$

$$E = \int_l (\vec{v} \times \vec{B}) \cdot \vec{dl} = Blv \tag{2}$$

If it is carrying a current "I", the element "dl" is subjected to a force:

$$d\vec{F} = (\vec{dl} \times \vec{B}) \cdot I \tag{3}$$

$$F = \int_l (\vec{dl} \times \vec{B}) \cdot I = BlI \tag{4}$$

If the conductor moves and, at the same time, some current is flowing, the electric power transmitted is equal to the mechanical power:

$$P_e = E \cdot I = B \cdot l \cdot v \cdot \frac{F}{B \cdot l} = F \cdot v = P_m \tag{5}$$

Consider, then, the evolution of the following phenomenon (the conductor is free to move):

- initial status: conductor stands still and no current is flowing

- a voltage V is applied, so an initial current begins to flow:

$$I_0 = \frac{V}{R} \tag{6}$$

- it generates an electromagnetic force on the conductor:

$$F_0 = B \cdot l \cdot I_0 \tag{7}$$

- the conductor accelerates, and this generates an induced electromotive force: $E = Blv$
- in every instants you have, then, that the current becomes:

$$I = \frac{V - E}{R} \tag{8}$$

- equilibrium is reached when the current vanishes and therefore when V = E

If braking forces go into action, then the balance is reached when $F_e = F_r$ and therefore the presence of a current is required. In particular:

$$F_r = BlI = Bl\frac{V - E}{R} = Bl\frac{Blv_0 - Blv}{R} = \frac{B^2l^2}{R}(v_0 - v) \tag{9}$$

$$v = v_0 - \frac{F_r \cdot R}{B^2l^2} \tag{10}$$

where "v" is always less than the no load speed v_o. What was said for the primitive linear machine remains valid for a rotating machine, making the appropriate substitutions:

- instead of the Bl product, the flux linkage Ψ has to be considered
- the electromagnetic force F_e becomes electromagnetic torque τ_e
- the linear speed v becomes angular speed ω
- the inertia force becomes inertia torque
- the braking force becomes braking torque.

The fundamental relationships then become:

$$E = \omega\Psi; \quad \tau_e = \Psi I; \quad P_E = EI = \tau_e\omega = P_m \tag{11}$$

We can thus obtain, in a similar way, the values of the operating speed:

- at no load (without braking torque)

$$\omega_n = \frac{V}{\Psi} \tag{12}$$

- with load (a braking torque is present)

$$\omega = \omega_n - \frac{\tau_r}{0.5 \cdot \Psi^2} \tag{13}$$

Torque-Speed Curve

The locus of the operation points (at steady state) of the electric machine is called torque/speed curve (Fig. 6). The remarkable points are:

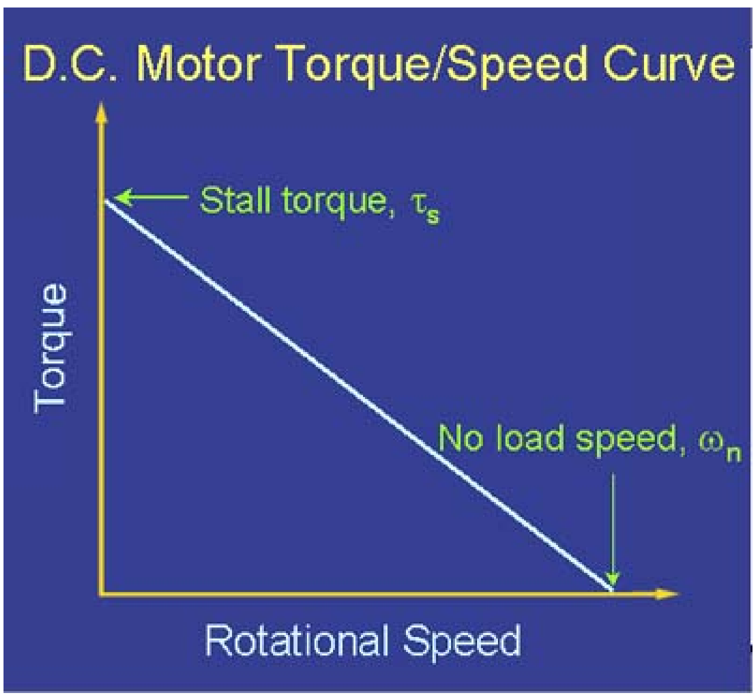

Figure 6: Plot of the torque-speed curve.

- the intersection with the torque axis (zero speed = standstill), which represents the start torque.

- the intersection with the speed axis (zero torque = no load), which provides no load speed.

The intersection of this curve with the torque/speed curve of the mechanical load identifies the operating point. This operating point may be stable or unstable. It will be stable if an increase of speed is a deficiency of torque so the machine slows down; conversely, a decrease of speed must be matched by a surplus of torque so the machine accelerates. Knowledge of the mechanical behavior of the load is a fundamental starting point for the drive design and for the choice of the machine to be used. By studying the behavior of the mechanical load, you can in fact identify the needs in terms of torque, starting from the time profile of the required speed. You may also obtain the points of maximum acceleration and deceleration, that are the points of maximum torque for the electric machine. Recall that earlier we defined power as the product of torque and angular velocity. This corresponds to the area of a rectangle under the torque/speed curve with one corner at the origin and another corner at a point on the curve. Due to the linear inverse relationship between torque and speed, the maximum power occurs at the point where $\omega = 0.5\ \omega_n$ or where $\tau = 0.5\ \tau_s$ (if the slope of the line is 45° the two rectangles coincide).

Reluctance torque

In this section we want to highlight the different parts that contribute to the electro-mechanical action. Basically there are two different cases:

- torque resulting from the magnetic structure of the circuit, that is caused by anisotropy
- resulting from the interaction between two magnetic coils.

Consider the first case, referring to Fig. 7, where you can highlight a magnetic structure made by a fixed part on which is mounted a winding and a rotating part. From the electrical point of view, the system can be represented by a one-port, as a series of a variable inductance

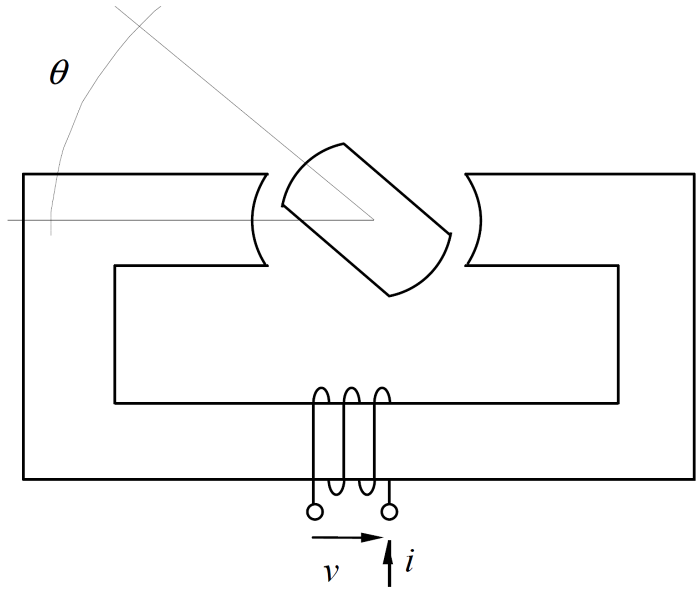

Figure 7: Simplified model of a electric motor.

with a resistance. Thus we have:

$$v = Ri + \frac{d}{dt}(Li) = Ri + L\frac{di}{dt} + i\frac{dL}{dt} \tag{14}$$
$$vi = Ri^2 + iL\frac{di}{dt} + i^2\frac{dL}{dt} \tag{15}$$

Recalling that the instantaneous power absorbed by the magnetic field can be obtained by differentiating the energy , it results:

$$p_i = \frac{dW}{dt} = \frac{d}{dt}\left(\frac{1}{2}Li^2\right) = Li\frac{di}{dt} + \frac{1}{2}i^2\frac{dL}{dt} \tag{16}$$

Comparing this expression with the energy balance of the circuit, we find that the total electric power inlet (on the left of the equation) is divided into three contributions:

1. power dissipated in the resistance: $p_p = Ri^2$
2. power related to the magnetic field: $P_i = Li\frac{di}{dt} + \frac{1}{2}i^2\frac{dL}{dt}$
3. mechanical power: $p_m = 0.5i^2\frac{dL}{dt}$

If we consider that the inductance in the reference frame varies with periodic sinusoidal pattern, you can highlight an expression for the anisotropy torque:

$$p_m = \frac{1}{2}i^2\frac{dL}{dt} = \frac{1}{2}i^2\frac{dL}{d\theta}\frac{d\theta}{dt} = \frac{1}{2}i^2\frac{dL}{d\theta}\omega \tag{17}$$

$$\tau_m = \frac{p_m}{\omega} = \frac{1}{2}i^2\frac{dL}{d\theta} \tag{18}$$

Now, suppose to change the old structure so as to include a new winding on the rotating part as in Fig. 8. The equations describing this structure are that of a mutual inductor with

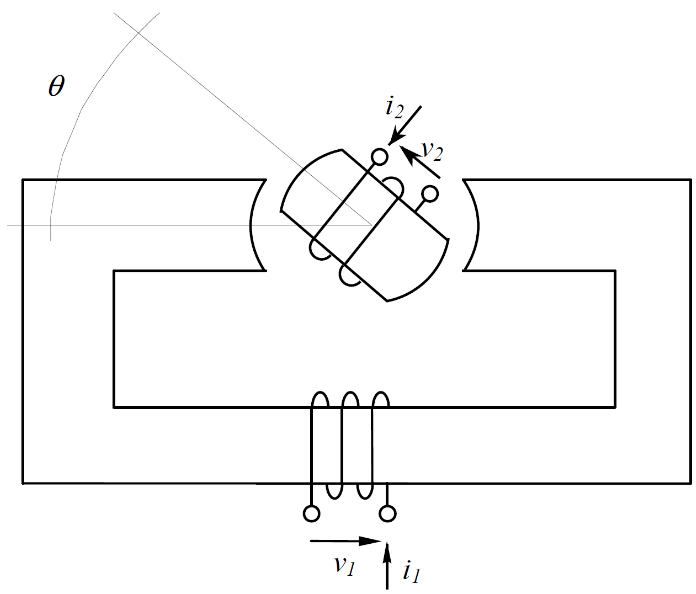

Figure 8: Modified model of a electric motor.

variable parameters. We can then write:

$$v_1 = R_1 i_1 + \frac{dL_1 i_1}{dt} + \frac{dL_m i_2}{dt} \tag{19}$$

$$v_2 = R_2 i_2 + \frac{dL_2 i_2}{dt} + \frac{dL_m i_1}{dt} \tag{20}$$

thus:

$$v_1 = R_1 i_1 + L_1 \frac{di_1}{dt} + i_1 \frac{dL_1}{dt} + L_m \frac{di_2}{dt} + i_2 \frac{dL_m}{dt} \tag{21}$$

$$v_2 = R_2 i_2 + L_2 \frac{di_2}{dt} + i_2 \frac{dL_2}{dt} + L_m \frac{di_1}{dt} + i_1 \frac{dL_m}{dt} \tag{22}$$

If, therefore, similar to what we saw before, we extract the contributions related to the mechanical power, it is obtained:

$$\tau_{1,m} = \frac{1}{2} i_1^2 \frac{dL_1}{dt} + \frac{1}{2} i_1 i_2 \frac{dL_m}{dt} \tag{23}$$

$$\tau_{2,m} = \frac{1}{2} i_2^2 \frac{dL_2}{dt} + \frac{1}{2} i_1 i_2 \frac{dL_m}{dt} \tag{24}$$

where the first two terms are similar to the previous terms of anisotropy and the last one is called excitation torque.

Motor nameplate and rated values

In order to be able to identify the characteristics of a machine it is necessary to see the nameplate that is located on the frame. This nameplate is a real ID card that allows us to trace the basic features of the machine with regard to the application point of view. The values reported on the plate depend on the type of machine, but they are able to provide the information for a proper connection and use. In particular the important parts of a motor are named:

- **stator**: part of the machine which remains stationary during operation
- **rotor**: part of the machine which is in rotary motion during operation
- **inductor winding**: winding that creates the main magnetic field
- **induced winding**: winding immersed in the field created by the inductor

Motor Control

Taken from Siciliano.

The electrical equilibrium of the motor is described by:

$$\begin{cases} V_a = (R_a + sL_a)I_a + V_g \\ V_g = k_v \Omega_m \end{cases} \tag{25}$$

- $V_a,\ I_a$ voltage and current of the winding (series of R_a and L_a)
- V_g is the counter efm, that is proportional to the angular velocity of the shaft Ω_m

The mechanical equilibrium is described by:

$$\begin{cases} C_m = (sI_m + F_m)\Omega_m + C_l \\ C_m = k_t I_a \end{cases} \tag{26}$$

- C_m, C_l are the electromechanic and resistance torques
- I_m is the inertia
- F_m is the viscous friction

The transfer function due to the power amplifiers is:

$$\frac{V_{out}}{V_{in}} = \frac{G_v}{1 + sT_v} \tag{27}$$

- G_v is the gain of the amplifier
- T_v is the time constant of the amplifier (neglectable, way faster than the other time constants)