Using estimation to optimize electric pump flow rates for spraying applications

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ABSTRACT

Electric pumps are widely used in applications such as sanitation, manufacturing and agriculture. Electric current is supplied to the pumps, which translates into a corresponding flow rate and therefore output pressure. This relationship between a pump's pressure and flow rate is described as its performance curve. This conference paper uses estimation theory and cognitive system techniques to improve the efficiency of electric pumps. Specifically, using the perception-action cycle to observe the states, predict the system behaviour and then optimize it. The system states are estimated using sensor measurements and system dynamics, where the control system uses the states to find the optimal flow rate based on the performance curve and adjust the system accordingly. This methodology is validated using simulations. The simulation models a sprayer that is powered by a DC motor where the ideal spray angle is maintained based on the distance to the surface. Optimizing the electric pump performance, reduces energy consumption and optimizes fluid usage, which can provide savings in many industries and systems.

Keywords: Estimation theory, Cognitive systems, Electric pumps, Optimizing electric pumps for spraying

1. INTRODUCTION

DC motors are the drivers in equipment including sprayers, water pumps, and fuel and oil pumps.[1–4] A DC motor is a common type of electric motor. It runs direct current through internal coils to generate an electromagnetic field. There are two common types of DC motors, brushed and brushless. Brushed DC motors have their coils in the center rotating around stationary magnets while brushless DC motors have a magnet in the center that rotates around the coils.[?] Regardless of the type of motor, the speed at which the motor spins depends on the current and the voltage inputted. In the context of pumps, the RPM of the motor drives the flow rate and thereby the pressure of the pump. The relationship between current, flow rate and pressure is outlined in the performance curves of the pump.

This paper aim to propose using estimation to optimize the spraying function of a DC motor pump. By determining the optimal pressure for a given situation, the amount of solution used by the pump can be reduced in the long term. The motivation is to improve the efficiency of the process by reducing the amount of solution needed to spray a surface. This process can be applied in manufacturing and solution process to reduce waste and increase efficiency.

In the information sheets for the pump, the information on the DC motor may be incomplete. There may also be discrepancies between the physical pump and the information outlined in the datasheet. This proves to be a challenge for simulations. Parameter estimation may be necessary to determine the characteristics of the motor. Research has been completed on various methods to estimate these parameters. One approach is to use multiparametric programming.[5] The nonlinear ODEs of the motor are transformed using the Euler method. The model parameters are then generated by setting optimal requirements and solving a system of parametric algebraic equations. Matlab and Simulink can be used as tools to estimate the parameters of the DC motors. Heck et al. uses the Simulink Parameter Estimation tool to estimate the required parameters. This is completed by measuring the current and RPM of the motor and inputting data into the Simulink tool.[6]

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Once the motor is running, it is also crucial to be able to estimate the state information of the system to perceive. A popular approach is using the Kalman filter. Jie Ding et al. uses a modified adaptive extended Kalman filter to update the process noise covariance matrix in real time.[7] Xu et ak utilizes the Extended Kalman Filter to make estimations of the speed and rotor position of a brushless DC motor. Brushless DC motors during motion can produce mechanical vibration, resonance and noise problems. It was determined that the EKF had suppressed the variances caused by the motor torque and different working conditions.[8] Tripathi et al found the EKF insufficient when the system is diverging and not well defined, so they used a Fractional Order Adaptive Kalman Filter (FOAFK), an adaptive state estimation technique which uses a fractional feedback loop of the previous Kalman gain and the current steady-state Kalman gain. By including the fractional derivative, the gain will never become unstable.[9]

Then the motors can be controlled based to better allocate its resources based on the inputs from its environment. Kottas et al. applies a fuzzy cognitive network to control a DC motor powered by a photovoltaic array (solar array).[10] They use the controller to determine the ideal load to be drawn based on the peak power that the array can provide at that time. Belgacem et al. use control on a pumping system of a photovoltaic array. The pumping system is controlled by a fuzzy logic controller as well as sliding mode control to observe and track the power so that the array is turned on when the highest power is extracted. Zhang uses a neural network fuzzy PID control method to study a brushless DC motor system. They demonstrate that the fuzzy PID control can improve the stability and control of the system. Zeng et al.[4] uses a speed-current double closed-loop control system to control an electric oil pump. The system observes the requirements and disturbances from the hydraulic system and pumps enough flow to keep an increasing oil pressure. Similarly, Gao et al. uses a torque-chain double-loop control scheme to determine the voltage to be applied for the required torque output.[11] Zhang et al.[12] uses adaptive control to make a system with a DC motor more stable. They use an STM32 to generate a PWM signal based on the speed of the motor, which then combined with the PID control algorithm to improve the robustness of the control system. Sliding mode control is also used by Dal with feedforward torque compensation and proportional error feedback control.[13] The combination of the three provided stabilized tracking of the rotor speed and current and improved the convergence of the speed estimate. Marrugo et al. combines a linear quadratic regulator (LQR) with a Kalman filter to control a DC motor. As the LQR requires many sensors, they are replaced with the state of the Kalman filter.[14] Komec aimed to move away from using PID controller and other control to focus on implementing cascade control to a DC motor. The simulations demonstrate that the system can respond quickly and is capable of rejecting disturbances when there is a change in load.[15]

2. MODELLING

The process for the simulation is as followed. The goal is to keep a consistent spray length (x) of 30 cm. As the distance between the nozzle and the surface (l) may change, the spray angle (θ) would need to adjust itself to keep the goal spray length (x) as seen in Figure 1.

First, the dc motor was mathematically modelled using Kirchhoff's voltage law.[16] It is assumed that the magnetic field is constant, then the motor torque is proportional to the current.

$$T = K_t i \tag{1}$$

The back emf of the motor is proportional to the rotational velocity of the motor.

$$e = K_e \dot{\theta}(t) \tag{2}$$

Then combining Newton's law with Kirchhoff's law, two equations can be made.

$$J\ddot{\theta} + b\dot{\theta} = Ki \tag{3}$$

$$L\frac{di}{dt} + Ri = V - K\dot{\theta} \tag{4}$$

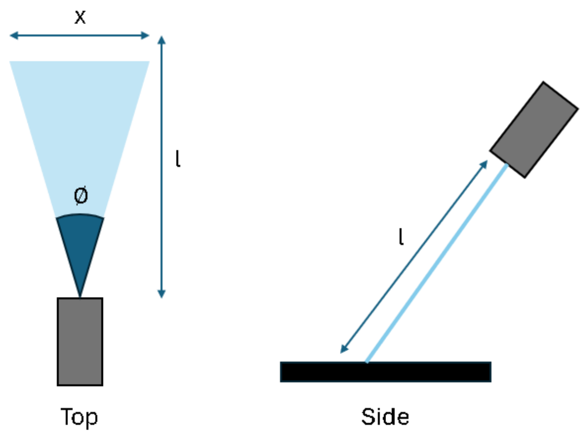

Figure 1. The top and side view of the spray simulation

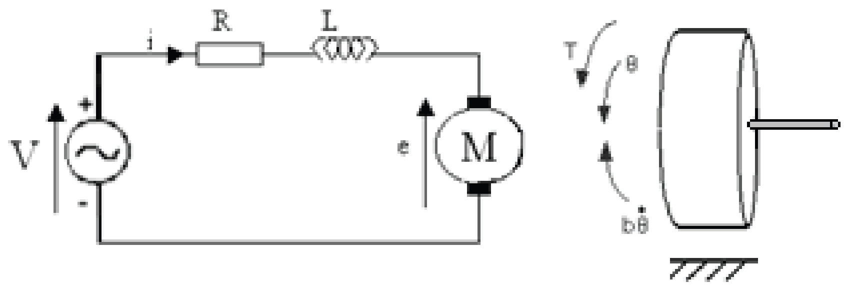

Figure 2. Diagram of DC Motor Circuit

Then using these equations, the state space model can be created.

$$\frac{d}{dt}\begin{bmatrix}\dot{\theta}\\ i\end{bmatrix} = \begin{bmatrix}-\frac{b}{J} & \frac{K}{J}\\ -\frac{K}{J} & -\frac{R}{L}\end{bmatrix}\begin{bmatrix}\dot{\theta}\\ i\end{bmatrix} + \begin{bmatrix}0\\ \frac{1}{L}\end{bmatrix}V \tag{5}$$

$$y = \begin{bmatrix}1 & 0\end{bmatrix}\begin{bmatrix}\dot{\theta}\\ i\end{bmatrix} \tag{6}$$

The pump uses the rotation of the motor to pressurize the liquid. This pressure relates to the flow rate of the liquid as well. This relationship is captured in the pump performance table is listed in the data sheet. An example of this performance table is shown in Table 1.[17]

Pressure (PSI)	Flow (GPM)	RPM (Min/Max)
Open	1.8	2300/2325
10	1.31	2260/2290
20	1.26	2215/2240
30	1.20	2175/2190
40	1.14	2130/2145
50	1.08	2085/2095

Table 1. Example of a Pump performance table for the Shurflo 800-543-136

To model this relationship, RPM and pressure values from the table were used to create an equation. The relationship was approximated to the linear function:

$$y = -0.25x + 575 \tag{7}$$

For the spray nozzle, the spray angle can change with the pressure, where an increase in pressure increases the spray angle. For this simulation, this performance relationship was simplified to a nozzle that has a spray angle from 0 to 60 deg in a linear relationship.

The process for this simulation measures the distance of the nozzle from the surface. It then calculates the ideal spray angle to maintain a spray length of 30cm. This angle is compared to the current angle and the pump pressure is adjusted using the input voltage. In this simulation a PID controller was used minimize the error between the ideal and current spray angle. The Kalman filter was used to estimate the state of pump and motor using a flow rate sensor.[18]

3. RESULTS & DISCUSSION

First the simulation was evaluated as a step response, where distance from the nozzle increases from 0 to 30cm. Figure 3 shows the response of the simulation. There is a significant initial overshoot, however it settles within 12 ms. Similarly, Figure 4 shows the response when the distance changes in a sine wave. After the initial overshoot, the response angle settles with the ideal angle with minimal error.

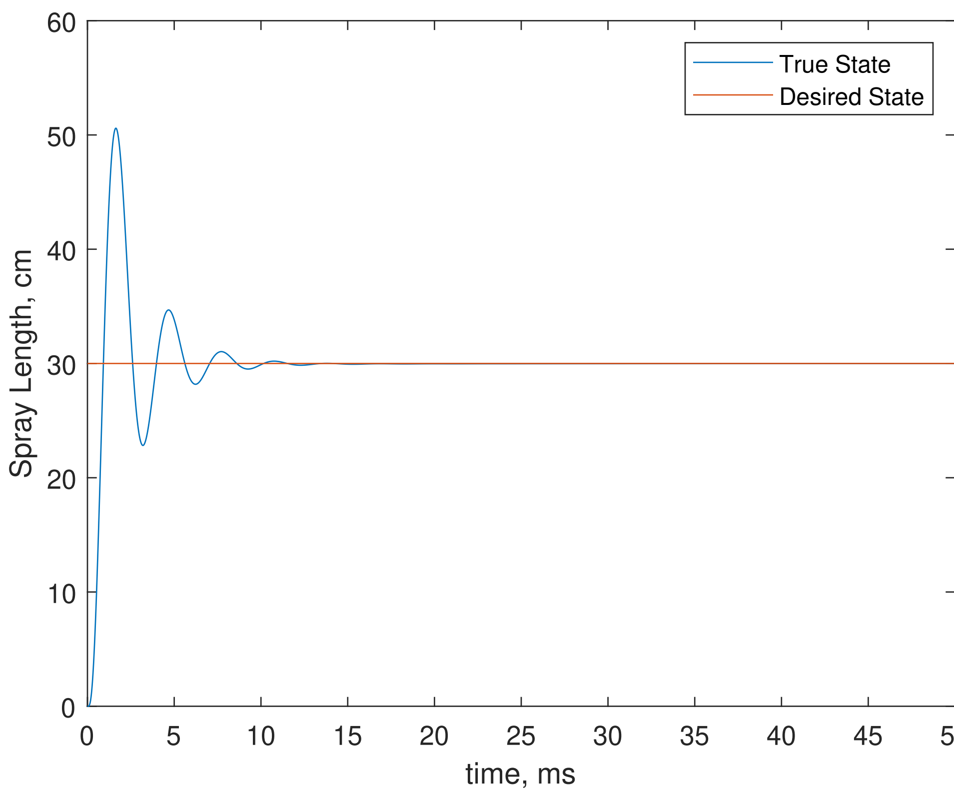

Figure 3. The step response of the simulation

The simulation shows a promising response. The control scheme is effective at matching the ideal angle set for spraying. However, as per any simulation, the response is only as good as the assumptions made. As with the Kalman filter assumptions, linearity is assumed to simplify the model. It is more likely that true model would be non-linear. Therefore, further investigation is required to model the system non-linearly. The simulation also uses a hypothetical nozzle with a specified range. For future work, using commercially available components for the entire simulation would increase the accuracy of the results.

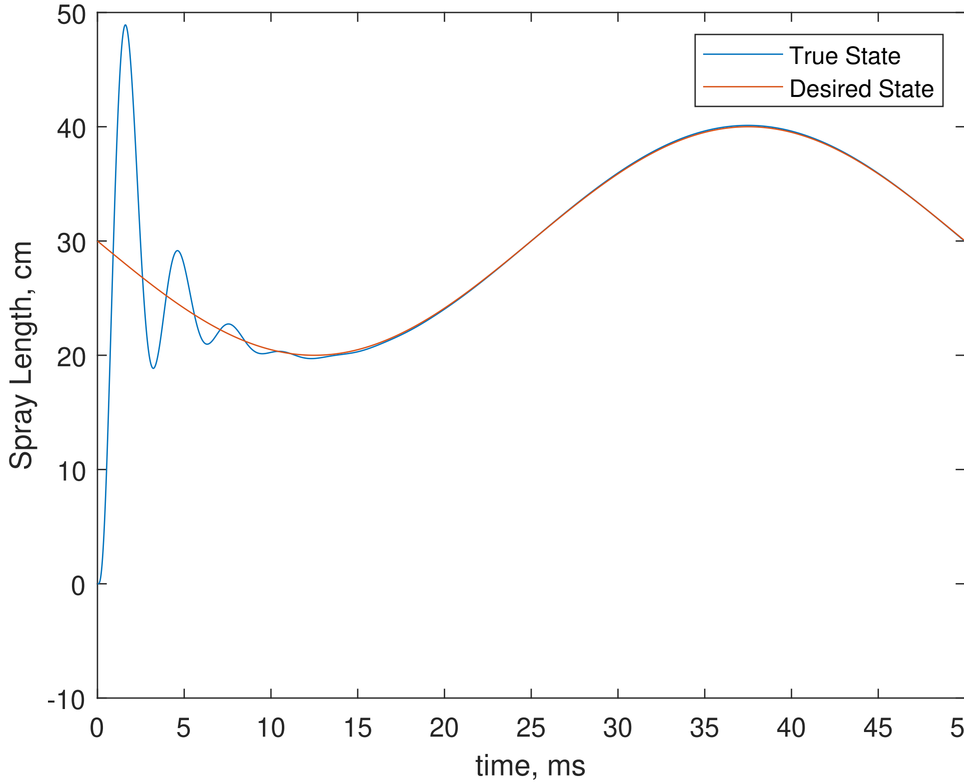

Figure 4. The response of the simulation based on a sin wave

4. CONCLUSION

This paper presented a simulation which optimized the DC motor for spraying applications. It adjusted its input minimize the error between the ideal spray angle and the current spray angle to maintain a consistent spray length. This simulation can be applied in any process that has consistent spraying processes. As the spray length stays consistent, it minimizes the wasted solution making the entire process more efficient.

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