Sensorless Field-Oriented Estimation of Hybrid Stepper Motors in High-Performance Paper Handling

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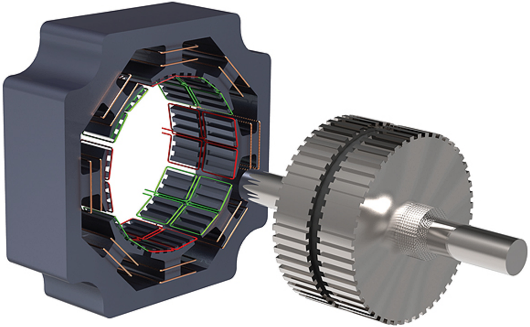
Hybrid stepper motor (HSM)

- **Two-phase HSMs used in direct-drive for printing applications**
- **Microstepping allows precise positioning**



Problem formulation

Open-loop control

- No feedback required
- Mechanical resonances
- Ohmic and iron losses $\rightarrow$ heat generation

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Sensorless Field-Oriented control (FOC)

- Requires feedback
- Significantly less mechanical vibration
- Efficient
- More flexibility (torque control, field-weakening)

Problem formulation

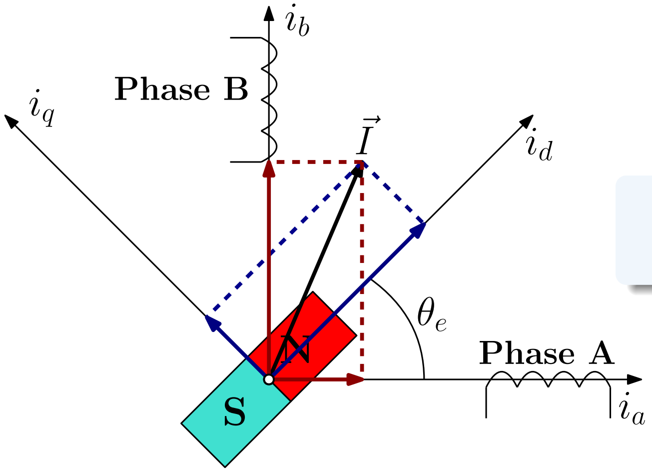
Research question

How can sensorless field-oriented control of a hybrid stepper motor be designed and implemented in high-performance paper handling?

Main criteria

- Achieve rotor position error < 3 electrical degrees (< 1 mrad mechanically)
- Operation range from 0 RPM to 700 RPM

How to model HSM: choice of reference frames



ab-**frame** $\xrightarrow{\text{park}}$ *dq*-**frame**

ab-**frame** $\xleftarrow{\text{inv. park}}$ *dq*-**frame**

How to model HSM: in rotating reference frame

HSM model in rotating reference frame

$$L\frac{di_d}{dt} = v_d - Ri_d + LN\omega_m i_q$$

$$L\frac{di_q}{dt} = v_q - Ri_q - LN\omega_m i_d - K_m\omega_m$$

$$J\frac{d\omega_m}{dt} = \tau_{em} - B\omega_m - \tau_L$$

$$\frac{d\theta_m}{dt} = \omega_m$$

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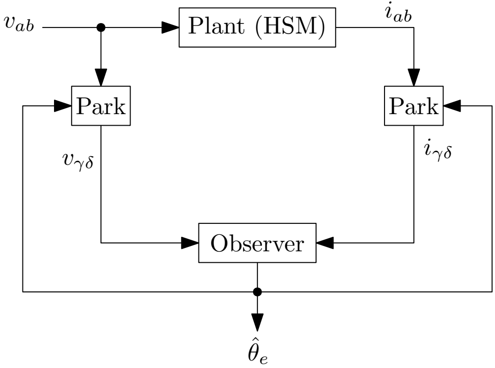
Electromagnetic torque is proportional to i_q

$$\tau_{em} = K_m i_q$$

Estimator Design: Luenberger observer in rotor frame



- Transform observer to rotating frame
- Observed back EMF is DC (at constant speed)

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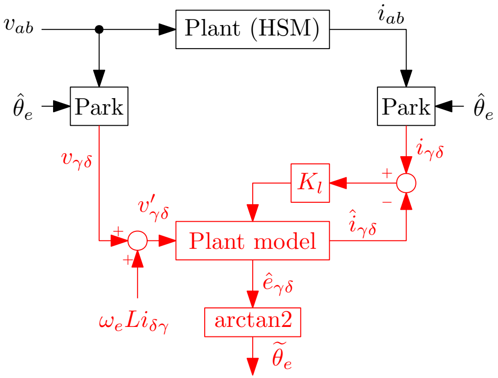

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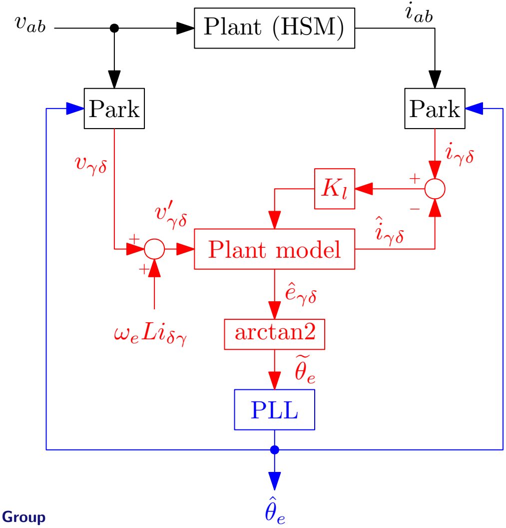

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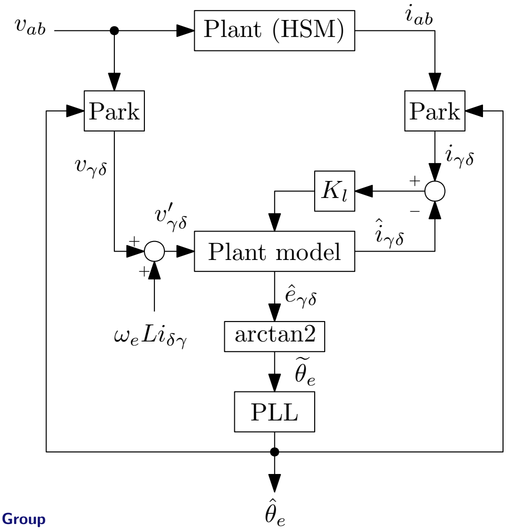

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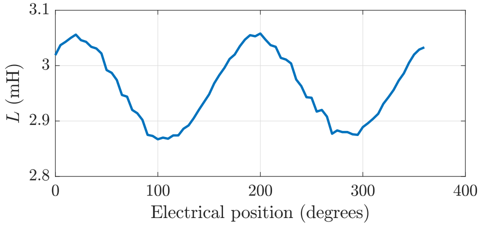
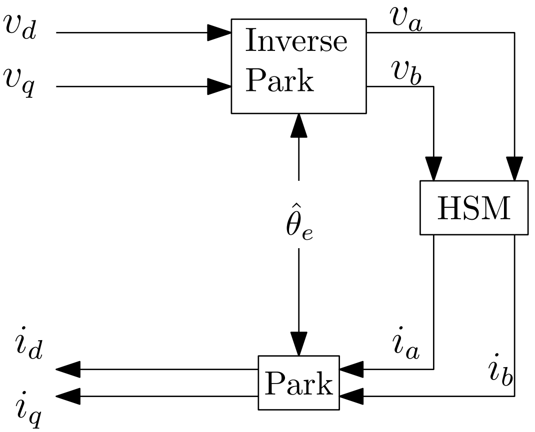
Low-speed estimator: saliency-based tracking

- **Phase inductance dependent of rotor position: Saliency**



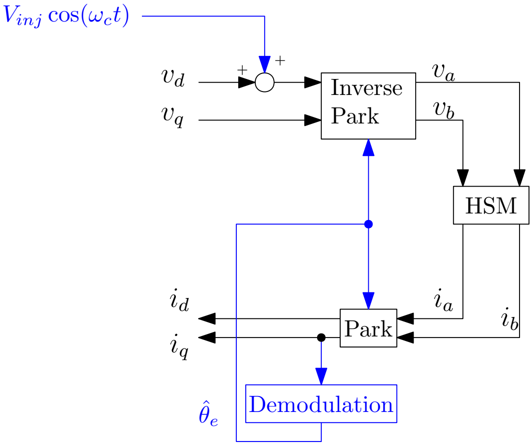
Inject high-frequent signal to obtain rotor position

Low-speed estimator: saliency-based tracking



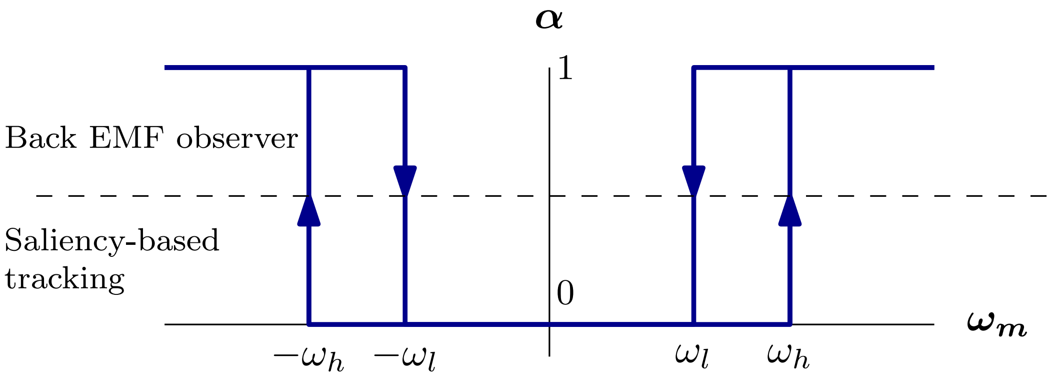
- Injection into d-axis to minimize torque ripple
- Retrieve rotor information from q-axis

Low-speed estimator: saliency-based tracking

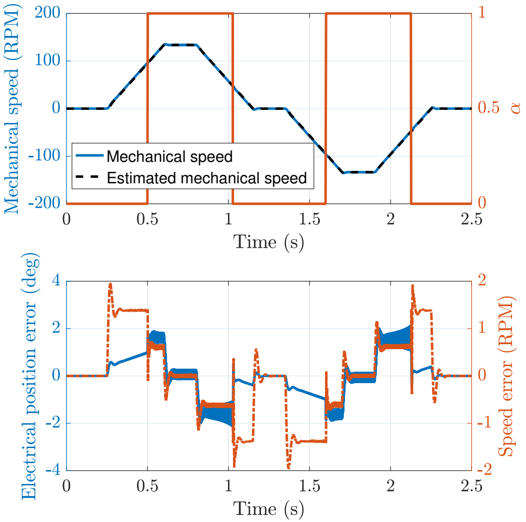


- Injection into *d*-axis to minimize torque ripple
- Retrieve rotor information from *q*-axis

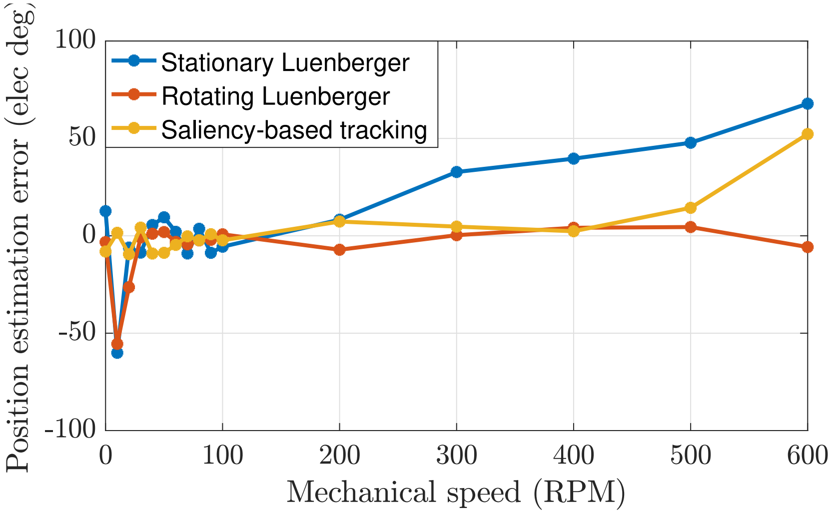
Combining the estimators: switching with hysteresis



Simulation: Combining the estimators



Mean error of different estimators



Experimental results

- Rotating Luenberger observer max average error: 7 elec. degrees (mid-to-high speed)
- Saliency-based tracking max average error: 9 elec. degrees
- Max speed: 660 RPM

Conclusions

Sensorless FOC can be designed and implemented for the HSM in high-performance paper handling by dividing the design in several stages

- HSM modeled in *dq*-frame for FOC design
- Position control realized with cascade control
- Rotating Luenberger observer designed for mid-to-high
- Saliency-based tracking designed for zero-to-low speed
- Switching rule with hysteresis to combine estimators

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Recommendations and future work

Recommendations for experimental setup

- Use dual H-bridge inverter configuration instead of a three-leg inverter
- Investigate saliency-based tracking closed-loop issues

Future work for sensorless FOC

- Extend control structure (Feed-forward, Field-weakening)
- Investigate observer performance under high load
- Switch between position control and torque control
- Analyze performance with paper handling setpoints

Thank You!