Modeling and Control of Inverted Magnetic Needle System: A New Problem in Control Theory

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by

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ABSTRACT

In this thesis, we propose a novel problem in the control theory involving the control of the magnetic needle in the presence of an external magnetic field. A magnetic needle when restricted to rotate about a single axis, will result in two equilibrium points, namely, (i) a stable equilibrium, when the field lines of the magnetic needle are aligned with the external field, and (ii) an unstable equilibrium, when the field lines of the magnetic needle are in opposition to the external field. This problem has some similarities with the classical inverted pendulum problem, both the systems have one stable and unstable equilibrium. The major difference is, in the case of pendulum system, equilibrium points are due to the Earth's gravity, which is almost uniform on the Earth's surface. But, in the case of the magnetic needle system, the equilibrium points are due to the external magnetic field, which can be uniform/non-uniform, introducing additional nonlinearities compared with the pendulum system.

In this thesis, at first, the nonlinear dynamics are derived for a 1-D inverted magnetic needle system using the Euler-Lagrange equation by considering the uniform external magnetic field. The system nonlinear dynamics are linearized at the unstable equilibrium. The design of various standard linear controllers (PD, PID, lead, lead-lag, H_∞, QFT) and their tracking performance for the linearized and nonlinear systems in the neighborhood of the unstable equilibrium are discussed in detail. The robust performance of these controllers in-terms of parameter uncertainty, disturbance are compared, based on the simulations.

In the experimental validation, we consider the detailed mathematical modeling of the proposed 1-D inverted magnetic needle system, which involves, the modeling of a non-uniform external magnetic field and its validation by experimental measurement of the magnetic needle dipole moment. A "First Order Sliding Mode Controller (FOSMC)" is used to achieve the control objectives. The simulation results are validated with the experimental results where, for achieving a close match, the sensor and actuator nonlinearities

are considered. Further, the system's robust performance are compared with Proportional-Derivative (PD), Proportional-Integral-Derivative (PID) controllers in the presence of system parameter uncertainty, disturbance, and sensor delay. We also study the effect of change in FOSMC, PD controller parameters, on the system performance. Further, robust performance of PD, FOSMC controllers are compared with measured random noise signal of different standard deviations.

As an extension of the 1-D system, we introduce a 2-D inverted magnetic needle system. Here, the magnetic needle is allowed to have two degrees of freedom to rotate in an external magnetic field. At first, the 2-D inverted magnetic needle system dynamics are derived using the Euler-Lagrange equation by considering the uniform external magnetic field. System tracking performance is studied for the linearized and nonlinear system and is compared for various standard linear controllers, in the neighborhood of its unstable equilibrium. The robust performance of these designed controllers is compared in the presence of parameter uncertainty. Further, the external magnetic field non-uniformity is modeled and validated with the measured data. Second, the 2-D inverted magnetic needle system dynamics are derived by considering the non-uniform external magnetic field. Various energy-based control strategies are explored based on the Lyapunov function, to improve the system transient and steady-state performance. Asymptotic stability of these control strategies is derived using the Lyapunov function. Their tracking performance near the unstable equilibrium is compared based on the simulations.