MECHATRONIC DEVELOPMENT OF AN IN-PIPE MICROROBOT WITH INTELLIGENT ACTIVE FORCE CONTROL

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To my beloved Atena

And my beloved Mother and Father

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ABSTRACT

In this research, the development of an in-pipe microrobot system with intelligent active force control (AFC) capability was investigated and presented, including both simulation and experimental studies. Three actuated microrobot mechanisms driven by pneumatic, piezoelectric and voice-coil actuators were modelled and simulated in a constrained environment inside a pipe. The mechanisms were then embedded into the proposed AFC-based control strategy. The worm-like movement of these microrobots with the respective actuators were effectively modelled using the impact drive mechanism (IDM). A classic proportional-integral-derivative (PID) controller was first designed and applied to the microrobot system to follow a desired trajectory in the presence of disturbances, which may be created due to the frictional force or fluid viscosity inside a pipe. Later, an AFC-based controller was utilized to enhance the system dynamic performance by robustly rejecting the disturbances. To estimate the inertial mass of the AFC loop, artificial intelligence (AI) techniques, namely the variants of fuzzy logic (FL) and iterative learning algorithms (ILA) were explicitly employed. The dynamic response of the fully developed model of the in-pipe microrobot systems (with three different actuators) subject to various input excitations and disturbances was rigorously explored and numerically experimented. This involved the parametric study and sensitivity analysis to observe and to analyse the effects of a number of influential parameters that were deemed to have positive impact on the system performance. The simulation work was validated through an experimental investigation performed on a rig prototype that employed the voice-coil actuated mechanism to drive the selected AFC-based microrobot scheme, considering the given operating and loading conditions. Full mechatronic approach was adopted in the design of the rig by integrating the related sensors, actuator, mechanical parts and digital controller in a hardware-in-the-loop simulation (HILS) configuration. Parametric study was carried out to complement the simulation counterpart by taking into account the different settings and working environments. From the experimental results, the developed in-pipe microrobot system was proven to be effective and robust in its trajectory tracking, in spite of the existence of various excitation inputs and external disturbances. This implied that the produced experimental responses were in good agreement with those acquired via simulation. The outcomes of the study shall provide a strong foundation for furthering the design of specific in-pipe microrobot applications, such as visual inspection of the inner surface of pipes, fault-diagnostics, obstacle removal and other related tasks.

ABSTRAK

Pembangunan satu sistem robot mikro dalam paip dengan keupayaan kawalan daya aktif pintar (AFC) telah dikaji dan dipersembahkan dalam kajian simulasi dan eksperimen. Tiga jenis mekanisme penggerak robot mikro, iaitu penggerak pneumatic, piezoelektrik, dan voice-coil telah dimasukkan ke dalam strategi kawalan berasaskan-AFC, dan disimulasikan seterusnya dengan mempertimbangkan beberapa operasi dan keadaan beban di dalam persekitaran paip yang terhad. Robot mikro yang mempunyai pergerakan seperti cacing telah dimodelkan secara efektif dengan menggunakan mekanisme penggerak hentaman (IDM). Pengawal klasik berkadaran-kamiran-terbitan (PID) telah direka bentuk terlebih dahulu dan diaplikasikan kepada sistem robot mikro untuk menjejaki trajektori kehendak dengan kehadiran gangguan akibat daripada daya geseran atau kelikatan cecair dalam paip. Kemudian, pengawal berasaskan AFC digunakan untuk meningkatkan prestasi sistem dinamik berdasarkan kekukuhannya untuk menangkis gangguan. Dalam penganggaran jisim inersia bagi gelung AFC, teknik kepintaran buatan (AI) melalui variasi logik kabur (FL) dan algoritma lelaran pembelajaran (ILA) telah digunakan secara khusus. Respons dan gerak balas dinamik bagi model sistem robot mikro dalam-paip yang telah dibangunkan sepenuhnya (dengan tiga penggerak berbeza) dan tertakluk kepada pelbagai ujaan masukan dan gangguan telah dikaji dengan rapi melalui eksperimen numerical (simulasi). Ini melibatkan kajian parametric dan analisis sensitiviti untuk memerhati dan menganalisis kesan beberapa parameter berpengaruh yang dianggap mempunyai kesan positif terhadap prestasis sistem. Sebahagian proses simulasi disahkan melalui kajian eksperimen ke atas prototaip rig yang menggunakan mekanisme penggerak voice-coil untuk memacu robot mikro berasaskan skema AFC, dengan mengambil kira operasi dan beban keadaan yang telah diberikan. Pendekatan mekatronik yang sempurna telah diguna pakai dalam merekabentuk rig, di mana alat penderia, penggerak, bahagian mekanikal dan pengawal digital telah diintegrasikan bersama melalui konfigurasi simulasi perkakasan di dalam gelung (HILS). Kajian parametrik dijalankan untuk mengambil kira persekitaran dan penetapan yang berbeza berpandukan simulasi sebelum ini. Keputusan eksperimen jelas menunjukkan keberkesanan penjejakan trajektori sistem robot mikro dalam-paip yang telah dibangunkan, walaupun terdapatnya pelbagai ujaan masukan dan gangguan luar. Ini dengan jelas menunjukkan bahawa keputusan yang dihasilkan melalui eksperimen fizikal mempunyai banyak persamaan dengna hasil simulasi. Hasil kajian menyediakan satu asas yang kukuh untuk memajukan reka bentuk yang spesifik untuk aplikasi robot mikro dalam paip seperti pemeriksaan visual permukaan paip, diagnostik kegagalan, penyingkiran halangan dan lain-lain tugas yang berkaitan.