Modified PID Control of Flexible Manipulators (フレキシブルマニピュレータの修正PID制御)

著者	Tamer Mohamed Mansour
号	53
学位授与番号	4014
URL	http://hdl.handle.net/10097/42428

	たまー　もはめっど　まんさわー
氏　　　　　名	Tamer Mohamed Mansour
授　与　学　位	博士（工学）
学位授与年月日	平成２０年７月９日
学位授与の根拠法規	学位規則第４条第１項
研究科，専攻の名称	東北大学大学院工学研究科（博士課程）航空宇宙工学専攻
学位論文題目	Modified PID Control of Flexible Manipulators (フレキシブルマニピュレータの修正 PID 制御)
指　導　教　員	東北大学教授　内山　勝
論文審査委員	主査　東北大学教授 内山　勝　　東北大学教授　吉田　和哉 東北大学教授 小菅　一弘　　東北大学准教授　近野　敦

論文内容要旨

The flexible manipulator started to play an important part in many engineering applications nowadays. Major advantages of flexible manipulators include small mass, fast motion, and large force to mass ratio, which are reflected directly in the reduced energy consumption, increased productivity, and enhanced payload capacity. In space application, the flexible manipulators are considered as an optimal alternative to the massive rigid manipulators.

Unlike the rigid manipulators, the difficulties facing the usage of flexible manipulators are numerous. The modeling of the flexibility of the manipulator is one of the challenges. The non-minimum phase problem, which appears from the modeling of the flexible manipulators, is also another challenge. It becomes a tough topic to find a controller able to deal with the flexibility of the manipulator and at the same time grantee the stability with vibration suppression ability. Therefore, the control of flexible manipulator has become a benchmark for new controllers to test their ability to deal with this complicated problem.

The precise and availability of the measured variables used in the control is another challenge. The control of flexible manipulators has been studied with great interest by many researchers over the past years due to its great benefits. To find a controller that can achieve the end effector position of the flexible manipulator in a short time in addition to a suppression of its vibration to be able to achieve the tasks is the main goal of the control of flexible manipulator in the free space. Although significant progresses have been made in many aspects over the last two decades, many issues are not yet resolved yet, and simple, effective, and reliable controls of flexible manipulators remain open requests.

In this thesis, a Modified Proportional-Integral-Derivative (MPID) controller is utilized to control flexible manipulator. This controller is mainly depends on the vibration feedback accompanied with a servo controller for the flexible manipulator joint. While different from other similar works, the controller uses the rate of the deflection of the tip as indication of the vibration. The controller utilizes the vibration feedback to generate a control signal able to achieve the final position while damping the vibration. In order to demonstrate the superior performance of the controller, the results are compared with those obtained by using the standard controllers like PD and PI. An analysis of the closed-loop performance composed of the joint angle and tip deflection is done in simulation and in experiment. From this analysis we can found that the proposed controller can suppress the vibration of the tip without causing an overshoot for the joint motion. Only three measurements needed to apply this controller, the measurements are the base joint angle $\theta(t)$, base joint velocity $\dot{\theta}(t)$ and the rate of deflection at the tip of the manipulator $\dot{\delta}(l,t)$ unlike other types of controller which needs full states measurements. Moreover, to ensure the performance of the proposed controller with the rate of deflection as a vibration signal, the stability of the controller is tested. The stability of the system is shown experimentally and theoretically when using the rate of deflection at the tip $\dot{\delta}(l,t)$ as the vibration signal in the controller. The stability is depend mainly of the derivative gain of the joint K_{jp} and will not be affected by the vibration feedback. Include the deflection effect in the controller enable generating a control signal take into consideration the effect of the end effector vibration. The generated control signal has the ability to achieve accurate tip position without neither overshoot for the joint nor vibration at the tip. The results show that the proposed controller can achieve stability while damping the vibration. When comparing the MPID with PI control in case study, the merits of using this control can be noticed. A 0.25 kg tip payload is used with ten degree step input for the joint angle, and tip position response shows that using the MPID gives a steady state error e_{ss} equals a value of ± 0.1 mm, while it reaches a value of ± 1.3 mm when using PI controller for the same step input. It is noticed from the response that the MPID has a desirable response especially near the steady state. After then the tip payload is increased to 0.5 kg and the tip response is recorded. In this case also the MPID gives a speedy rise time, t_r for the response of the tip position equals 0.95 s and e_{ss} equals ± 0.2 mm while the PI shows rise time, equivalent to 1.23 s and steady state error ±2.0 mm.

As for the measuring of the vibration variable, a visual data utilizing a camera- which becomes an inherent part of space manipulators- is used to evaluate the vibration variable. Using the camera to measure the rate of deflection makes the strain measuring circuits and strain amplifiers unnecessary. By this way a remarkable reduction in the apparatus used in measuring the end effector vibration of the flexible manipulator. The MPID controller, which is studied in the previous part, is implemented experimentally to a space manipulator moving vertically to suppress the end effector vibration. The experimental step, which is used in the verification, is analyzed. The mathematical model for the manipulator is driven then the MPID controller is revised to be used with the manipulator to suppress the vibration. The MPID vibration suppression control based on the feed back of the rate of change in deflection is combined with a visual measurement. The novelty of the results lies in the fact that the measurement of the rate of change in deflection, which is used as a vibration variable, has been done without the need of numerical differentiation. The rate of change of deflection is estimated using an observer based on Kalman filter. Also by this way their will be no need for the strain measuring circuits and instruments as the camera which had become an essential part of today manipulator is utilized to get the vibration feedback signal. The detailed of the estimation of the vibration signal is explained. A comparison between finding the vibration signal using the strain, using the visual information is done, and it shows superior trends especially in the issue of noise re-movement in addition to needless of numerical differentiation. Finally an experimental verification for the MPID is done. For the results the MPID combined with the visual data for the vibration successfully damp the vibration of the end effector while archiving an accurate position for the joint of the manipulator. An observer based on Kalman filter is developed to find the rate of deflection directly without the need of mathematical differentiation. The new combination achieved a successful replacement to the old method for measuring the deflection of the flexible manipulator. For the effect of the MPID as a vibration suppression, when we use only PD controller in the MPID (i.e. $K_m = 0$) the root mean square (RMS) of the first mode of deflection equals 0.801×10^{-3} m. After activation of the vibration term by setting the value of modified gain K_m to 350 s/m^2 the value of the RMS of the first mode of deflection is reduced to 0.5×10^{-3} m. For the second mode of vibration of the end effector, the values of root mean square error are 0.131×10^{-3} m and 0.121×10^{-3} m for the MPID with $K_m = 0$ and $K_m =350$ respectively. For the vibration variable, the rate of change in deflection, a value of 0.0178 m/s for the root mean square is obtained for the first mode of vibration when only PD controller is used. A reduction with about 35 % of the amplitude of the RMS is achieved if the vibration variable is used in the controller. The value of the RMS when using the MPID with K_m equals 350 s/m^2 is 0.0117 m/s while for the second mode of vibration, the values of the RMS is reduced by 13 % when using the MPID with the vibration variable. The value of the RMS becomes 0.0151 m/s when imposing the vibration variable while it was 0.0169 m/s while using only PD controller. Also, it is noticeable that using the vibration feedback has some enhancement also on the joint movement and it reaches its reference position without overshoot. The MPID succeeded to suppress the vibration of the flexible manipulator.

The tuning of controller gain for flexible manipulators has not been tried using the neural networks before. The main contribution in this chapter is to make an adaptive system, which can generate the optimum modified gain for the MPID controller, is achieved. The modified gain of the controller is optimized using neural network algorithm. The contribution of the proposed algorithm is that it takes into account the effect of payload for the end effector when optimizing the gain for the MPID. Also, it will not need to make a tuning for the gains of the joint as it will generate the optimum gain corresponding to gains of the joint whatever its values.

In this part, the MPID controller is used with the single-link flexible robot. This controller uses a few measurements and mainly depends on vibration variable. The aim for make an adaptive system which can generate the optimum modified gain for the MPID controller is achieved. The modified gain of the controller is optimized using neural network algorithm. A two hidden layer neural network using the scaled conjugate gradients method in the learning is used. The neural network found the optimum gain corresponds to the tip payload, joint angle, the proportional and derivative gains of the controller. Test for the neural network shows that it can give the same relationship between the modified gain and the criteria function in addition to the enormous saving in time. The main advantage of the NN approach is the considerable low computational cost to find an optimal gain with different tip payload. The results also include the response using the optimum gain located by the neural network. The results show the effectiveness of using the neural network to find the optimum gain for the controller.

In this thesis, a controller that improves the response of the flexible manipulator without the massive need of measurements is proposed. The target from the control of the flexible manipulator is to make the joint motion converges to final position fast while effectively suppressed the elastic vibration of the end effector of the manipulator. The idea of the controller comes from the importance need to include the effect of the vibration effect of the end effector in the generated control signal, which drives the flexible manipulator. The visual data is effectively used to evaluate the vibration variable which is used in the controller. The neural network is utilized to find the optimum gain for the proposed controller.

論文審査結果の要旨

フレキシブルマニピュレータは，軽量であること，それゆえ自重に対する可搬重量比が高いこと，エネルギー消費が少ないこと，など多くの利点を持ち，これまで数多くの研究がなされてきた。しかし，フレキシブルマニピュレータには，軽量化のために構造剛性が低下し，運動時に振動が発生するという問題があった。この振動問題を解決するために，リンク先端の弾性変位，またはリンク根元の弾性歪みをフィードバックし，振動を抑制する制御法が開発されている。しかし，これらの手法では，重力などにより静的な弾性変位が生じる場合，それが振動抑制制御に悪影響を及ぼすという問題があった。本論文は，この問題を解決するために，リンク先端の弾性変位速度をフィードバックする振動抑制制御則を提案し，実際のフレキシブルマニピュレータに応用したもので，全編5章からなる。

第1章は序論であり，本研究の背景及び目的を述べている。

第2章では，弾性に起因するリンク先端の速度をフィードバックする修正PID制御則について論じ，制御系の安定性を解析したのち，その有効性をシミュレーションと実験で検証している。制御則を実際のフレキシブルマニピュレータに応用し，実験によりその有効性を確認している点が評価できる。

第3章では，フレキシブルマニピュレータに搭載された手先カメラ画像から，アームの弾性変位に起因するリンク先端の速度を推定し，修正PID制御に応用する手法について論じ，その有効性を実験により確認している。宇宙用マニピュレータは打ち上げコストを低減するために，軽量化され，したがって，フレキシブルマニピュレータとなるが，宇宙での過酷な環境から，弾性変位計測のために歪みゲージを用いることは困難である。一方，宇宙用マニピュレータのほとんどが手先カメラを搭載しており，本章で提案する手法は，宇宙用マニピュレータに振動抑制制御を適用するための有用な手法となる。これは重要な成果である。

第4章では，第2章で論じた修正PID制御則における最適なフィードバックゲインを，ニューラルネットワークを利用して決定する手法を提案している。動力学シミュレーションを行って最適なフィードバックゲインを求める方法は，時間がかかりすぎ，オンライン応用には適しない。これに対し，本章の手法は，動力学シミュレーションの結果をニューラルネットワークで学習する手法であり，最適なゲインを探索する時間が劇的に短縮され，オンライン応用が可能である。この手法は，実用上，非常に興味深い。

第5章は結論である。

以上要するに本論文は，フレキシブルマニピュレータに対し，リンク先端の弾性変位速度をフィードバックする振動抑制制御則を提案し，さらに，この制御則に対し，リンク先端の弾性変位速度を手先カメラ画像から求める手法及び最適なフィードバックゲインをニューラルネットワークにより決定する方法を提案し，これらの手法の有効性を示したもので，提案された振動抑制制御則，振動計測手法，最適ゲインの決定法の汎用性を考慮すると，航空宇宙工学及びロボット工学の発展に寄与するところが少なくない。

よって，本論文は博士（工学）の学位論文として合格と認める。