An Automatic Screw Tightening Shaft Based on Enhanced Variable Gain PID Control

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Abstract—In this paper, a modular designed automatic screw tightening shaft system, which is based on enhanced variable gain PID control, is proposed. Designed for the autonomous screw tightening operation, the screw tightening shaft enjoys huge potential for industry application. The screw tightening shaft and the screw tightening process are both mathematically modeled as an uncertain feedback system because of the uncertain properties. And the control performance is verified by choosing proper controller parameters that the closed loop system is stable on the basis of the Routh stability criterion whereas the torque tracking error exponentially converges to a small residue. Furthermore, it can be seen from the simulation and experiment results on the screw tightening shaft system that the proposed autonomous system is valid and effective.

Keywords- Modular design; automatic screw tightening shaft (ASTS); pre-tightening force; PID control; variable gain

I. INTRODUCTION

In the assembly industry, screw connection is one of the most prevalent connection method, in which impact wrench plays an important role [1-3]. Nevertheless, in the process of using impact wrench to screw-in or screw-out screws from screw hole, an operator is required, which means that the adequacy of the pre-tightening torque and effectiveness of the assembly process are determined by the operator's experience. And screw damage or dropping off may be caused by improper pre-tightening torque. Therefore, a highly reliable and efficient automatic screw tightening machine is essential in the modern assembly industry.

As we know, the pre-tightening force is the most important parameter in the process of screw tightening, which is a static force that makes the screw fasten on the screw hole without looseness [4, 5]. In practice, it is required that the torque should be slightly adjusted to ensure sufficient pre-tightening force but not damage the screw. Because of the differences of screws and working conditions, even a skilled operator can hardly fasten all the screws with proper force. Although an operator can easily determine the alignment when puts a screw on the screw hole, it is not so easy a job for an automatic machine. Therefore, to avoid damages to the screw and screw hole, a control method or a mechanical way is required to learn the alignment.

Currently, PID (proportional-integral-derivative) control is the most commonly used control method [6-8], which is well accepted in practical use and shows good performance on linear systems. Nevertheless, the screw tightening process is of uncertainties and non-linear due to the tightening friction between the screw hole and screw, material of the screw and screw hole, tightening condition, and environmental temperature, and accordingly the dynamics of ASTS. Thus, a simple PID controller with fixed values of proportional, derivative and integral gains may be unable to offer the required tightening performance [9].

In the past several decades, the approximation based control [10] using fuzzy logic systems (FL) and neural networks (NNs) [11, 12] has been widely applied to the nonlinear systems with unknown dynamics [13-15], because of its universal approximation capability over certain compact set. Due to the NNs and FL's superb capacity [16] in handling complex systems with unknown dynamics, the related techniques have also been adopted to solve control problems in practical systems, including robotic manipulator [17], screw connection [18] and wheeled inverted pendulum [19]. And to control screw tightening, several approaches and algorithms have been proposed in several studies. In [9, 18], a model-free fuzzy control method is proposed. In [20], a preload control method is presented, and a mathematical model was proposed to predict the friction-compensated control torque. Moreover, in [21], an angle control method was proposed.

However, although the precious studies [22], [5], [9], [20], [21] were all contributed significantly to screw tightening, they neglected the mechanical flexibility while designing the screw tightening tool. And to the best of the...
authors’ knowledge, there is no significant study reported to integrate the tightening process and screw tightening shaft to be a control model. In the screw tightening industry, the mechanical flexibility of screw tightening tool is significant, and better control performance may be realized by more precise control model. For the first time, a modular designed automatic screw tightening shaft (ASTS), which can detect misalignment between screw and screw hole, is proposed in the paper. The ASTS can screw the screw to specified torque even when the screw deviates 5mm from screw hole. The model of ASTS is considered to be a DC servo motor connected with a reducer. Moreover, an model-based enhanced variable gain PID controller is designed, combining with the tightening process. The control target is to make the tightening torque achieve the given torque. It is verified by the numerical simulation and practical experimental results that the proposed control method is valid and effective.

Then, the rest of the paper is organized as follows. In section 2, the modular design of screw tightening shaft system is presented; In section 3, the ASTS control model is illustrated; In section 4, the enhanced variable gain PID control is described; In section 5 and 6, the effectiveness of the proposed control is validated by simulation and experimental results, and the last section, namely Section 7, is the conclusion of the paper.

II. MODULAR DESIGN OF THE ASTS

From Figure 1, it can be seen that the ASTS proposed in this paper is mounted on an automatic opening-sealing device used to automatically open and seal a 400L metal drum. And the ASTS is applied to screw automatically after the screw or screw hole was located. As shown in Figure 2, the screw tightening shaft structure, takes the servo motor as power unit, the reducer and coupling as transmission components, and the photoelectric sensor and dynamic torque sensor as real-time torque detection units. Moreover, at the front end, the spring, induction plate, adjusting sleeve and the front end sleeve are made to be adapted to the adjustment of screw. The spring and the adjusting sleeve have a certain degree of stretching freedom, and thus the tightening of the screw can be facilitated and the shaking of the screw can be avoided. Meanwhile, as a cardan joint, the front end sleeve can adapt to different angles of screw deflection, making the deviation of screws falls within 5mm. Moreover, all of the four modules can be easily removed and replaced.

Once the positioning screw is fixed, the screw would be unable to insert into the front end sleeve if the front end sleeve of ASTS deviates over 5mm from the screw. In this case, the spring of the adjusting module will be compressed, leading the induction plate to raise, and then due to the approaching of the induction plate, the photoelectric sensor will send out an alarm signal, with the tightening of screws stopped. However, if the deviation of the front end sleeve from the screw is less than 5mm, the screw can be set into the front end sleeve successfully, and then the tightening of the screw can be done smoothly, thanks to the flexibility of the adjusting module.

In practical application, tightening torque and specified tightening angle are given to the tightening indicator. And for the ASTS mentioned in this paper, its specified angle is of 2160 ±10%, in order to avoid screw jamming when tightening the screw. In other words, the angle sensors and torque give feedbacks of screw tightening angle and screw tightening torque to the controller respectively, which stops the ASTS once the screw tightening torque reaches the desired torque but the screw tightening angle is not. Several rules are defined to prevent screw jamming from happening, based on the relationship between screw tightening torque and screw tightening angle. Meanwhile, the adaptability of ASTS mechanism keeps screw jamming from happening, too.

III. THE SHAFT CONTROL SYSTEM

Based on the model of screws and nuts, the tightening indicator is given a constant tightening torque. Thus,

Figure 1. ASTS at Center for Robotics, UESTC

Figure 2. ASTS Component (a) Servo motor (b) Speed reducer (c) Coupling (d) Torque & angle sensor (e) Fixing pedestal of tightening shaft (f) Spring (g) Photoelectric sensor (h) Induction plate (i) Adjusting sleeve (j) Front end sleeve.
controlling the ASTS to reach the given tightening torque becomes the control target. It can be seen in Figure 3.

![Figure 3. Control Block Diagram.](image)

In the tightening process, there are three key variables, namely pre-tightening force, screw turning angle and tightening torque [5, 22, 23]. The relationship between the pre-tightening force and screw turning angle can be seen in Figure 4. In Figure 4, the relationship between the pre-tightening force and screw turning angle can be seen. The tightening process can be divided into four stages: the idle stage, plying-up stage, linear stage and over yield point stage, which are indicated as OA segment, AB segment, BC segment and CD segment respectively in Figure 4.

In the idle stage, pre-tightening force does not exist because at the beginning of the tightening process, the screw and screw hole have no contact. In the plying-up stage, the pre-tightening force grows rapidly when the screw and screw hole are contacted. Nevertheless, in this stage, it is hard to predict the rotation turns of the screw. Once the screw and screw hole are connected completely, the pre-tightening force demonstrates a linear relationship with the turning angle of the screw, which is called the linear stage. And the over yield point stage begins when the screw reaches the point of plastic deformation. In this stage, the pre-tightening force decreases while the turning angle of screw increases. This stage is harmful to the screw and connected target. Thus, in practical application, the tightening torque is controlled in the linear stage. Meanwhile, as one of the most efficient screw tightening methods, the torque-angle method adjusts the output torque to achieve linear stage first and then controls the turning angle to realize the given torque in the linear stage. In real operation, as the idle stage and plying-up stage of ASTS are very transient, we assume that the tightening process happens in the linear stage.

In the linear stage, it can be known that

\[ T = KF \theta \]  

and

\[ F = C_s S_p \theta / 360 \]  

where \( T \) and \( F \) are the tightening torque and pre-tightening force respectively; \( K \) is the real variable required to be confirmed by engineering tests; \( \theta \) and \( d \) are the turning angle of screw and nominal diameter of the screw respectively, and \( C_s \) and \( S_p \) are the system stiffness and the screw pitch respectively. From this equation, all the variables and functions without extra declaration are all time dependence.

Based on both (1) and (2), the relationship between tightening torque and screw turning angle can be defined by

\[ T = KDdC_s S_p / 360 = K'\theta \]  

where \( K' = KDdC_s S_p / 360 \) is the unknown torque-angular coefficient should be confirmed by trial. Actually, because \( C_s \) and \( S_p \) are both constants, variable \( K' \) is only affected by \( K \), which is made to be a variable by the comprehensive coefficient of friction. Thus, \( K \) almost equals to an unknown constant when the comprehensive coefficient of friction varies little. It can be seen from (3) that there is an approximate linear relationship between the screw turning angle and the tightening torque.

B. ASTS Control model

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The ASTS can be seen as a DC servo motor geared into a reducer. Moreover, the equation of electromagnetic torque of DC servo motor can be expressed as

\[ T_e = K_i i \]  

and the mechanical motion equation can be represented as

\[ T_e - T_i = J\omega_s + B\omega_a \]  

Meanwhile, the equation of the armature circuit voltage-equilibrium of DC servo motor is given as

\[ u = Ri + L\Delta i + K_i \omega_a \]  

where \( T_e \) is the electromagnetic torque; \( K_i \) is the torque constant; \( i \) represents the armature circuit current; \( T_i \) is the load torque to the motor axis; \( \omega_a \) is the mechanical angular velocity of the motor; \( J \) means the total equivalent moment of inertia to the motor axis; \( R \) is the
armature circuit resistance; \( B \) is the motor viscous damping coefficient; \( L \) and \( K_v \) are the armature circuit inductance and back electromotive force constant respectively; and \( \Delta \) and \( u \) are the differential operator and armature circuit voltage respectively.

With an \( n: 1 \) reducer in the ASTS, the load torque can be defined by (3) as

\[
T_e = \frac{T}{n},
\]

(7)

where \( \omega_i \) is the ASTS end effector angular velocity. Then according to (3), there is

\[
\dot{T} = K_v \omega_i.
\]

(9)

Substitute (4), (7), (8) to (5), and it can be obtained that

\[
\dot{\omega}_i = \frac{1}{J} (B \omega_i + \frac{T}{n^2}) + \frac{K_v}{Jn} i
\]

(10)

Combining (6), (9) and (10), then the ASTS control model can be rewritten as

\[
\begin{align*}
\dot{T} &= K_v \omega_i, \\
\dot{\omega}_i &= \frac{1}{J} (B \omega_i + \frac{T}{n^2}) + \frac{K_v}{Jn} i \\
\Delta i &= -\frac{R_i}{L} - \frac{nK_v}{L} \omega_i + \frac{1}{L} u
\end{align*}
\]

(11)

where \( n \) means the reduction ratio of the ASTS reducer.

IV. ENHANCED VARIABLE GAIN PID CONTROLLER DESIGN

For a normal variable gain PID controller, its fundamental thought is to match the cumulative velocity of integral value with the magnitude of deviation. The integral action reduces to nothing to prevent integral saturation when the system deviation is large, whereas it reinforces to improve the stability of velocity when the system deviation is small. What is more desired is to match the magnitude of proportional part reinforces to enhance the dynamic performance of system when system deviation is large whereas it reduces to prevent overshoot when system deviation is small. In this paper, an enhanced variable gain PID control method based on improving the variable gain PID control method.

A. Enhanced Variable gain PID method

The proportional and integral term of enhanced variable gain PID control algorithm can be expressed as

\[
u(k) = (k_p + x[e(k)]) e(k) + k_i \sum_{i=0}^{k-1} e(i)
\]

(12)

where \( k_p \) and \( k_i \) are the proportionality gain and integral gain of regular PID control method respectively. \( T \) is the sampling time. \( x[e(k)] \) and \( y[e(k)] \) are the functions of deviation \( e(k) \). As \( e(k) \) increases, \( x[e(k)] \) increases and \( y[e(k)] \) reduces accordingly. As \( e(k) \) reduces, \( x[e(k)] \) reduces and \( y[e(k)] \) increases accordingly.

The expression of \( x[e(k)] \) can be described as

\[
x[e(k)] = \begin{cases} 
 k_{p1}, & |e(k)| \leq \epsilon_1 \\
 k_{p2} - \frac{k_{p2}}{\epsilon_2} (|e(k)| - \epsilon_1) + k_{p1}, & \epsilon_1 < |e(k)| \leq \epsilon_1 + \epsilon_2 \\
 k_{p2}, & |e(k)| > \epsilon_1 + \epsilon_2
\end{cases}
\]

(13)

where parameters \( \epsilon_1 \), \( \epsilon_2 \), \( k_{p1} \) and \( k_{p2} \) are needed to be confirmed, and \( 0 \leq k_{p1} < k_{p2} \). On one hand, the chosen values of these four parameters must satisfy the condition of system stability. On the other hand, the chosen values of \( \epsilon_2 \) and \( k_{p2} \) must meet the condition of faster torque (controlled object) rise, whereas those of \( \epsilon_1 \) and \( k_{p1} \) must meet the condition of no torque overshoot.

The value of \( y[e(k)] \) varies between \([k_{ii}, 1]\) . When \( |e(k)| \leq \epsilon_1 \), the integral term is the same as the general, in order to increase the integral action to the highest and accumulate the current value of \( e(k) \) . When \( \epsilon_1 < |e(k)| \leq \epsilon_1 + \epsilon_4 \), the value of \( y[e(k)] \) which falls between \([k_{ii}, 1]\), varies with the magnitude of \( |e(k)| \) and the integral term accumulates part current value of \( e(k) \) . Thus, the value of integral velocity is in the range of \([k_{ii}T \sum_{i=0}^{k-1} e(i), k_{ii}T \sum_{i=0}^{k-1} e(i)] \) . When \( |e(k)| > \epsilon_1 + \epsilon_4 \), the value of \( y[e(k)] \) is equal to \( k_{ii} \), to reduce the integral action to lowest or to stop the accumulation of current value of \( e(k) \).

In order to enlarge the regulation range of enhanced variable gain PID controller, the values of parameters \( \epsilon_1 \), \( \epsilon_2 \), \( \epsilon_3 \) and \( \epsilon_4 \) must be decided by the maximum deviation value after the desired value variation are not fixed. Thus, (15) can be obtained.
(15)
\[
\begin{align*}
  e_1 &= e_{\text{max}} | n_1 \\
  e_2 &= e_{\text{max}} | n_2 \\
  e_3 &= e_{\text{max}} | n_3 \\
  e_4 &= e_{\text{max}} | n_4
\end{align*}
\]

where $e_{\text{max}}$ is the maximum deviation value between the desired value and feedback value after the desired value of controller input changes. Parameters $n_1$, $n_2$, $n_3$ and $n_4$ should be confirmed, which must satisfy $0 < n_i < 1$, $i = 1, 2, 3, 4$ , $0 < n_i + n_j < 1$ and $0 < n_i + n_j < 1$. First of all, their values all must satisfy the condition of system stability. Secondly, the chosen value of $n_i$ must meet the condition of rapid torque rise, and that of $n_j$ must meet the condition of no torque overshoot, and that of $n_k$ must meet the condition of no integral saturation and torque overshoot, and that of $n_l$ must meet the condition of rapid torque stabilization.

Finally, the enhanced variable gain PID controller is obtained as
\[
\begin{align*}
  u(k) &= (k_p + x[e(k)])e(k) \\
  &+ k_i \sum_{i=0}^{n} e(i) + y[e(k)]e(k)T \\
  &+ k_d \frac{e(k) - e(k-1)}{T},
\end{align*}
\]

where $k_d$ is the differential term gain. Because the enhanced variable gain PID controller required parameters $k_{p1}$, $k_{p2}$, $k_{i1}$, $m_1$ , $m_2$ , $m_3$ and $m_4$ should be inaccurate, the values can easily be confirmed.

B. Controller Design

It can be learn in Figure 5 the transfer function block diagram of automatic screw tightening shaft (ASTS). In Figure 5, $\frac{1}{T_w s + 1}$ is the transfer function of DC servo motor in which $T_w$ is the electrical and mechanical time constant of DC servo motor. $C(s)$ is the transfer function of enhanced variable gain PID controller.

\[
G(s) = \frac{1}{T_w s + 1} \frac{K^*}{s}
\]

The differentiation element of PID control method, which is sensitive to the noise of input signal, is not used in the system with more noise. Thus, only PI control is used in the loop controller. The transfer function $C(s)$ is written as
\[
C(s) = \frac{s(k_p + x[e(k)]) + k_i y[e(k)]}{s}
\]

where $k_p$ and $k_i$ are the proportionality gain and integral gain of traditional PID control algorithm respectively. Moreover, there are $k_{p1} \leq x[e(k)] \leq k_{p2}$ and $k_{i1} \leq y[e(k)] \leq 1$ , in which $k_{p1}$, $k_{p2}$ and $k_{i1}$ are unknown parameters of enhanced variable gain PID controller.

Therefore, the close loop transfer function of the system, as shown in Figure 5, can be obtained as
\[
\Phi(s) = \frac{C(s)G(s)}{1 + C(s)G(s)} = \frac{(k_p + x[e(k)])s + k_i y[e(k)]}{K^* s^3 + \frac{T_w}{K^*} s^2 + (k_p + x[e(k)])s + k_i y[e(k)]}
\]

Here, Routh stability criterion is adopted to judge the stability of the closed loop control system, which is described as
\[
\begin{align*}
  k_{p1} &> \frac{T_w}{K^*} - k_p \\
  k_{i1} &> 0
\end{align*}
\]

The stability of the system can be guaranteed by choosing appropriate values of parameters $k_{p1}$ and $k_{i1}$ to satisfy the criterion when design the controller for ASTS based on enhanced variable gain PID controller.

V. SIMULATION

To validate that the enhanced variable gain PID control method enjoys a better control performance, a series of simulations and experiments will be conducted in the next two sections. The real ASTS model parameters used in the simulations are demonstrated in Table I.

In this simulation, the unknown torque-angular constant coefficient is set as $K^* = 0.173$. Meanwhile, in all the simulations the desired torque is set to be $50Nm$, and the control input $u$ falls between $[-45.2,45.2]$.

Through debugging the model with the parameters of ASTS described above, the proportional and integral gains can be obtained, which are of 0.85 and 23.35 respectively.
and the value of parameters of enhanced variable gain PID controller are: $k_p = 3.2$, $k_i = 4.15$, $m_1 = m_2 = 0.06$, $m_2 = 0.08$, $m_3 = 0.24$, $k_{p1} = k_{p2} = 4.15$ and $k_{i1} = 0.01$. Thus, according to Routh stability criterion, the system stability is guaranteed by $k_{p1} > T_0 / K$ and $k_{i1} > 0$.

### TABLE I. PARAMETERS OF THE ASTS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_s$</td>
<td>Rated power of DC servo motor</td>
<td>400W</td>
</tr>
<tr>
<td>$U_s$</td>
<td>Rated voltage of DC servo motor</td>
<td>48V</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Rated torque of DC servo motor</td>
<td>1.27Nm</td>
</tr>
<tr>
<td>$n_s$</td>
<td>Rated speed of DC servo motor</td>
<td>3000rpm</td>
</tr>
<tr>
<td>$J$</td>
<td>Equivalent moment of inertia</td>
<td>0.000457kg·m²</td>
</tr>
<tr>
<td>$B$</td>
<td>Viscous damping coefficient</td>
<td>0.03Nm/(rad/s)</td>
</tr>
<tr>
<td>$L$</td>
<td>Reactance of DC servo motor</td>
<td>0.0036H</td>
</tr>
<tr>
<td>$R$</td>
<td>Resistance of DC servo motor</td>
<td>1.25Ω</td>
</tr>
<tr>
<td>$K_e$</td>
<td>Constant for back electromotive force</td>
<td>0.0753V/(rad/s)</td>
</tr>
<tr>
<td>$K_t$</td>
<td>Torque constant</td>
<td>0.49N·m/A</td>
</tr>
<tr>
<td>$T_w$</td>
<td>Electrical and mechanical time constant</td>
<td>0.53ms</td>
</tr>
<tr>
<td>$n$</td>
<td>Reduction ratio</td>
<td>100</td>
</tr>
</tbody>
</table>

### B. Simulation Test with Different Maximum Tightening Speed

In this simulation, the influence of screw tightening speed on torque accuracy is explored. The real rated speed of the DC motor is 3000rpm which is constant in all the simulations. To illustrate the influence of angular velocity, three maximum angular velocities are adopted in this simulation to tune the reduction ratio $n$ of the reducer. The value of the maximum angular velocity for ASTS corresponding to the tuned reduction ratio $n$ is shown in Table III. Furthermore, due to the unlimited armature circuit current in this simulation, which cannot be realized in real operation, the screw tightening torques do not decrease with the reduction of $n$. The screw tightening torques corresponding to the different $n$ are shown in Figure 7, and the simulation results are shown in Table IV.

From Figure 7 and Tables III-IV, it can be seen obviously that the torque accuracy of screw tightening is not decreased with the reduction of $n$ changing, i.e., the torque accuracy of screw tightening does not decrease with high speed. It means that with the enhanced variable gain PID controller, the accuracy of tightening torque can be guaranteed within a wide tightening speed range.

### Table II. Simulation Results with Different Controller

<table>
<thead>
<tr>
<th>Controller</th>
<th>Tightening time</th>
<th>Maximum torque/Final torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular PID controller</td>
<td>13.1s</td>
<td>51.2Nm/50.375Nm</td>
</tr>
<tr>
<td>Variable gain PID controller</td>
<td>10.2s</td>
<td>50Nm/50Nm</td>
</tr>
<tr>
<td>Enhanced variable gain PID controller</td>
<td>9.1s</td>
<td>50Nm/50Nm</td>
</tr>
</tbody>
</table>

### Table III. Different Speeds of the ASTS

<table>
<thead>
<tr>
<th>Reduction ratio</th>
<th>Maximum angular velocity of the ASTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>100:1</td>
<td>180°/s</td>
</tr>
<tr>
<td>50:1</td>
<td>360°/s</td>
</tr>
<tr>
<td>10:1</td>
<td>1800°/s</td>
</tr>
</tbody>
</table>

From Figure 6 and Table II, it can be seen obviously that with the shortest tightening time and no overshoot, the enhanced variable gain PID controller has the best control performance. The experiment test will be conducted below.
VI. EXPERIMENT

Two tests were conducted to verify that the controller is effective. In test 1, four controllers were applied to the ASTS to see the difference. In test 2, three maximum ASTS tightening speeds were set to demonstrate the variation of tightening accuracy with different tightening speeds. The ASTS tightening process is shown in Figure 8.

A. Test 1: Performance Comparison with Different Controller

In this test, two kinds of constant speed controllers and regular PID controller were adopted to compare with the enhanced variable gain PID controller. The ASTS end effector rotation speed were set as 180°/s and 90°/s respectively in the two kinds of constant speed controller. For the PID controller, the proportional, derivative and integral gains were obtained by trial and error. And the target of screw tightening torque was set to be 50 Nm. In this test, thirty trials were conducted. However, due to space limitations and as a similar trend could be found in all of the

results of the thirty trials, only one group of the results is selected to illustrate the different control performance in Figure 9. The average screw tightening torque and screw tightening time of each controller are presented in Table V.

It can be known from the test results that the final value of tightening torque is much higher than that of the set torque when adopting constant speed control with high motor speed. However, the tightening of screw with constant speed control is slow when motor speed is low, and the phenomenon of over-torque still exists. The PID control method shows a better output performance but the screw tightening speed is also slow and the final torque is of 51.04 Nm. Nevertheless, the enhanced variable gain PID controller can achieve precise control of torque while ensuring the tightening speed. It is worth saying that the over-torque cannot be avoided even with the enhanced variable gain PID controller due to the processing technics of the screw and the accuracy of the torque sensor.

TABLE V. PERFORMANCE PARAMETERS OF DIFFERENT CONTROLLER

<table>
<thead>
<tr>
<th>Controller</th>
<th>Average screw tightening time</th>
<th>Average screw tightening torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant speed controller (with speed of 180°/s)</td>
<td>11.4s</td>
<td>70.105 Nm</td>
</tr>
<tr>
<td>Enhanced variable gain PID controller</td>
<td>17.5s</td>
<td>50.125 Nm</td>
</tr>
<tr>
<td>PID controller</td>
<td>23.56s</td>
<td>51.04 Nm</td>
</tr>
<tr>
<td>Constant speed controller (with speed of 90°/s)</td>
<td>26s</td>
<td>53.275 Nm</td>
</tr>
</tbody>
</table>
different speeds on tightening accuracy. Similar to test ten times with each speed, in order to identify the effects of with the proposed controller, the ASTS tightens the screw set to be the maximum rotation speed respectively. Then, sealing devices is investigated. First, a modular designed screw tightening shaft mounted on automatic opening-

In the paper, a PID control method for an automatic

tightening time for a small enhancement (of 0.2% improvement) of tightening accuracy. Moreover, it is also clear seen from this experiment that it is not worthwhile to exchange a substantial increase (of 142% increase) of the maximum tightening speed. However, it can be seen from Figure 10 and Table VI that the accuracy of the proposed control method is influenced less by the different maximum tightening speeds than that of the constant speed control.

TABLE VI. PERFORMANCE PARAMETERS OF DIFFERENT MAXIMUM TIGHTENING SPEEDS

<table>
<thead>
<tr>
<th>Maximum tightening speed</th>
<th>Average screw tightening time</th>
<th>Average screw tightening torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>180° / s</td>
<td>17.5s</td>
<td>50.125Nm</td>
</tr>
<tr>
<td>120° / s</td>
<td>31.46s</td>
<td>50.085Nm</td>
</tr>
<tr>
<td>90° / s</td>
<td>42.35s</td>
<td>50.025Nm</td>
</tr>
</tbody>
</table>

B. Test 2: Variation of Tightening Accuracy with Different Maximum Tightening Speeds

In this test, due to the rated torque of the ASTS motor, and because we cannot use the method, which improves the rotation speed of tightening shaft by reducing the reduction ratio, adopted in subsection V-B, the rated rotation speed of the ASTS motor is set to be the maximum rotation speed. And the rotation speed of 180° / s, 120° / s and 90° / s were set to be the maximum rotation speed respectively. Then, with the proposed controller, the ASTS tightens the screw ten times with each speed, in order to identify the effects of different speeds on tightening accuracy. Similar to test 1, only one representative set of results is used for demonstration, as shown in Figure 10. Meanwhile, the mean value obtained in the thirty trials is as shown in Table VI.

It can be seen from Figure 10 and Table VI that the accuracy of the screw tightening reduces with the upgrading of the maximum tightening speed. However, it can be clearly seen from this experiment that it is not worthwhile to exchange a substantial increase (of 142% increase) of tightening time for a small enhancement (of 0.2% improvement) of tightening accuracy. Moreover, it is also indicated that the proposed controller has good control accuracy for a wide range of tightening speeds.

VII. CONCLUSION

In the paper, a PID control method for an automatic screw tightening shaft mounted on automatic opening-sealing devices is investigated. First, a modular designed automatic screw tightening shaft composed of adjusting module, monitor module, transmission module and drive module is introduced. Then, combined with the tightening process, a three order controlled object with unknown parameters is obtained. To realize the good control performance of the tightening process with an unknown time varying parameter, an enhanced variable gain PID control method is adopted. The modular design helps to ensure that there is a certain degree extent of physical flexibility in the tightening process and a stable and accurate control effect is guaranteed by the enhanced variable gain PID control. At last, it is verified that the proposed control method are effective and efficient, based on the simulation and experimental results. The performance is shown as follows:

1) The proposed control method can achieve high-accuracy torque even when part of the parameters of screw tightening model are unknown;
2) compared to the regular PID control, the proposed control method requires a shorter tightening time to achieve a higher tightening precision;
3) under the same dynamic conditions, the tightening accuracy of the proposed control method is influenced less by the different maximum tightening speeds than that of the constant speed control.

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