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ORIGINAL ARTICLE

A staged haptic rendering approach for virtual assembly of bolted joints in mechanical assembly

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Abstract

Haptic rendering in virtual environment provides a powerful training and validation tool for assembly of bolted joints that require accurate assembly forces. This work proposes a staged haptic rendering approach for virtual assembly (VA) of bolted joints. Firstly, by analyzing the stress condition during the actual assembly process, four consecutive stages, namely navigation stage, transition stage, linearity stage, and yield stage, are identified. Then, the force rendering model is set up. Moreover, a prototype VA system is developed to implement and test the approach. Two groups of experiments on a two-stage gear reducer are conducted to verify the feasibility of the approach and evaluate the prototype's performance. The results have shown that the force calculated by the proposed approach is consistent with the actual assembly and the evaluators are highly positive on the immersion and the guiding ability of the VA process with the haptic rendering provided.

Keywords Virtual assembly · Haptic rendering · Bolted joints

1 Introduction

Bolted joints are widely applied in structures and industrial machines due to their ease of assembly and disassembly. Other than the clamping load, bolted joints may take externally applied forces as well; hence, their reliability is vital to ensure the performance and safety of the machine. To ensure accurate clamping forces to be applied requires professional assembly knowledge and experiences, which are often acquired on-the-job or through expensive training processes that are not affordable to the industry most of the time.

Fortunately, with the advances in virtual reality technology, virtual assembly (VA) provides a power tool for assembly training and validation. In VA applications, operators can assemble virtual representations of physical models by simulating actual human behaviors and part interactions in virtual environment to make more encompassing design/assembly decisions, for which, intuitive and accurate human-computer interaction is the key for a successful VA process [1]. Other than common visual interaction modality, force/haptic feedback offers a novel approach to allow operators feel the force through the haptic device [2, 3]. Accurate force feedback not only improves realistic interaction but also is crucial to ensure accurate assembly of connections like bolted joints that take load for their performance. However, few work has been reported yet for simulating the forces in VA, not even to say those for bolted joints. Therefore, it is necessary to develop a force rendering approach to provide realistic force feedback for VA of such joints.

This paper is organized as follows: section 2 reviews some of the related works on VA systems with haptic feedback and introduces research for bolted joints in mechanical assemblies; section 3 analyzes the sequential assembly stages for bolted connection and then presents the haptic rendering approach. In the following section, section 4, design of the VA prototype system and case studies with two groups of experiments are described. And discussions on the results are presented. The last section, section 5, concludes the work.

2 Related works

The importance of force/haptic feedback in VA application has been demonstrated by several research works. Corbett [4] studied the effect of haptic feedback and visual distraction

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on pointing task performance in a three-dimensional virtual environment. The result indicated that a strong positive effect of haptic feedback on performance in terms of less task time and reduction of root-mean square error of motion. Sagardia [5] also did similar study and found out that with force feedback, the collision force yielded is significantly smaller than that with visual feedback. Hence, a higher assembly precision can be achieved. Other researchers studied the virtual force feedback approach for VA of different industry applications. Li [6] proposed a novel force feedback model for virtual robot teaching of belt lapping. The model mainly simulates the contact force when the part is polished by the belt on the contact wheel. The force may come from colliding and resistance effect between the part and the belt and acts at particular contacting point. Wang [2] studied the assembly force of mechanical assembly based on three basic mechanical fit types, namely the interference fit, transition fit, and clearance fit, and presented a novel force rendering approach, which calculates the assembly force by analyzing the tolerance variation between two mating parts along the assembly length. The assembly path is along a linear direction, such as a peg-in-hole task.

However, assembly force simulation for bolted joints does not belong to these categories, since their assembly paths are more complex and input torque applied varies with different stages of assembly. The ultimate research aim for simulating the force is to find the torque-angle correlation, thus providing accurate assembly torque. Chen [7] simplified the assembly process of bolted joints into three steps, namely identification, interactive positioning, and operation, while for the last two steps, operator will feel the force and motion constraints. Penalty method ($f = k \times x$) is applied to estimate the guiding force at the step of "interactive position," and also for the constraint force at the step of "operation." In the method, x is the vector from current position of haptic proxy to its nearest projection position on Archimedes screw and k is a penalty factor. Though the method is quite straightforward, it is more of a simplified force calculation approach, which may not be coincide with the actual load condition. Common bolted joints take both clamping load and external applied force; hence, when tightening the joint, the force taken by the bolt may not follow a unique linear correlation with its position changes. More specifically, at the beginning and the end of the tightening process, the force varies. As a matter of fact, many other research works have focused on torque-tension control methods, to find out the force condition at the end of the tightening process, where the bolt material is yielding, so as to determine the total torque or force needed to control the process. Fukuoka [8–10] dealt with the tightening process of elastic angle control method and took the effects of surface roughness of contact surfaces and the inclined angle existing around nut loaded surface into consideration based on traditional torque angle control methods, then proposed a novel expression relating axial bolt force and nut rotation angle. Sayed [11] proposed a new formula for the bearing frictional torque using four different scenarios of the contact pressure distribution under the turning fastener head or nut, and analyzed the effect of the varying radial sliding speed over the rotating contact surface. As the fastener torque-tension relationship is highly sensitive to the friction coefficients, Croccolo [12] provided an experimental methodology useful to determine the friction coefficients in bolted joints. Dario [13] studied the screw used in high-duty bolted joints and deduced a comprehensive and clearly structured view about the maximum equivalent stress acting on the bolt as a function of the actual joint parameters.

As reviewed above, with the unique advantages of VA for assembly training, there are quite some works trying to formulate the assembly forces for different machining processes and common assembly structures. However, for important connections, such as bolted joints that are applied in most of the machines, research works only studied the assembly force from mechanical aspect; there is little work reported for their performance and training in VA. Moreover, all the torque/force analysis focused on a certain stage or tried to determine the tightening torque value of the bolted joints. While in a VA process, user's operation is a complete ergonomically interactive process, which emphasizes the perceived authenticity of the entire assembly process. Therefore, it is necessary to analyze the overall bolted joint assembly into different stages so as to provide a more realistic haptic rendering approach for VA of bolted joints.

3 The staged haptic rendering approach

Overestimating the clamp load will result in overstressing the thread. And hence, the connection failed with thread slipping. Conversely, it may lead to joint separation, fastener loosening, or fatigue failure under cyclic loads [14]. Therefore, the haptic supplementation for bolted joints in the VA system needs to analyze the variation of the input torque during the actual assembly process. According to the different stress properties of bolted joints, the tightening process can be divided into four stages: navigation stage, transition stage, linearity stage, and yield stage. More specific torque-angle relationship of the four stages can be shown in Fig.1.

The theoretical assembly torque equation at each stage is then deduced as follows. To better illustrate the equations and parameters, the actual bolted joints used in the case study is adopted here as an example; its components and the values of basic parameters are in Fig. 2 and Table 1, respectively.

3.1 The navigation stage

This stage starts with fastening the nut onto the bolt shank and ends when the nut touches the surface of the gasket (Fig. 3) to

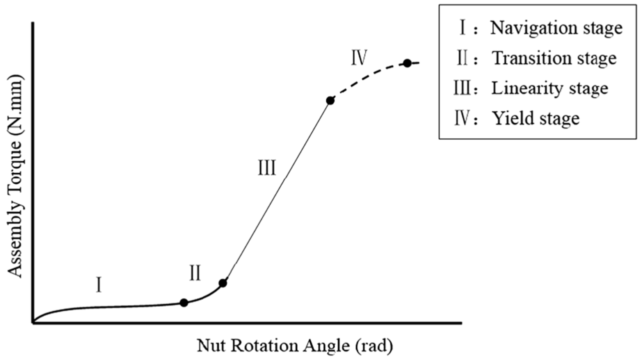


Fig. 1 The variation process of assembly torque

be fastened. During this process, the operation only needs to overcome the frictional torque between threads of bolt and nut. This torque can be calculated with the helix angle of the thread. Moreover, in this work, the influence of assembly/disassembly direction is also considered. As shown in Fig. 3, the stress analysis of nut with different assembly directions (illustrated by speed v) is different.

Hence, the assembly torque can be described as follows:

$$T = -G \times (\sin\alpha \pm \mu \times \cos\alpha) \times \frac{d_2}{2} \quad (1)$$

where G denotes the gravity of the nut and α denotes the helix angle, μ is the frictional coefficient between male and female threads, and d_2 represents the pitch diameter of thread.

So taking the bolted joint in Fig. 2 as the example, the torque for it at this stage is as follows:

$$T = -33.3 \times 9.8 \times 10^{-3} \times \left(\sin\left(30^{\circ}\right) - 0.3 \times \cos\left(30^{\circ}\right)\right) \times \frac{14.7}{2}$$

$$= -0.588 \ (N{\cdot}\text{mm})$$

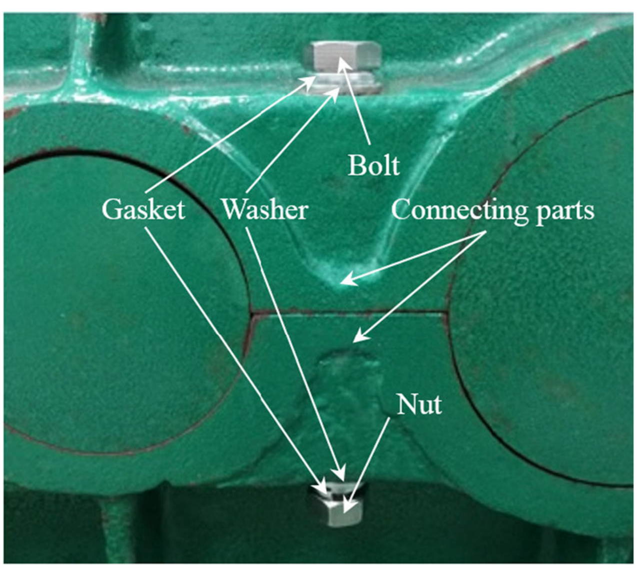


Fig. 2 The experimental object based on the bolted joint assembly

3.2 The transition stage

The transition stage is when the nut gets gradually tightened; during this process, every two contact surfaces of the bolted joints, i.e., the contacting surfaces between the nut and the surface of the part (such as a gasket) and the two contacting surfaces of the parts to be fastened, experience from initial condition of getting into contact to the final condition of contacting with pressure in-between. So the overall assembly torque required contains two parts, one is the torque to overcome the friction between screw threads, T_1, and the other is the one to overcome the friction between contacting surfaces, T_2.

The calculation of the frictional torque between screw threads at this stage is similar to that at the navigation stage (Eq. 1), and it is presented as follows:

$$T_1(t_i) = -\left(G \pm F_c^{'}(t_i)\right) \times (\sin\alpha \pm \mu_2 \times \cos\alpha) \times d_2$$

where μ_2 represents the frictional coefficient between male and female threads.

For the other part, T_2, it is caused by the clamping force during the process. The clamping force is generated and gradually increased when the rough surfaces of the parts pressing each other, and it is transferred onto the contacting surfaces between the nut and the surface of the part (Fig. 4).

Hence, the clamping force between two rough surfaces can be calculated according to the contact force model of the rough surfaces [15], which is described as follows:

$$F_c(t_i) = A(t_i) \times \frac{E^* \times h'}{\kappa}$$

where $A(t_i)$ represents the contact area of rough surfaces, which could be simulated based on the measurement of the fractal surface on the connecting parts; κ denotes the dimensionless constant and its value is 2 in common; h' represents the root of mean square (RSM) gradient of the surface profile h; and E^* is the only parameter to describe the elastic response; it can be calculated by $\frac{1}{E^*} = \frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2}$, v_1 and v_2 represent the Poisson ratio of the connecting parts, and their Young's modulus are represented by E_1 and E_2, respectively.

The frictional torque acting on the nut face can then be calculated:

$$p(t_i) = \frac{F_c^{'}(t_i) \pm G}{\frac{\pi}{4} \times \left(D_1^2 - D_2^2\right)}$$

$$T_2(t_i) = -\pi \times p(t_i) \times \mu_1 \times \int_{D_2}^{D_1} r^2 \times dr$$

where $F_c^{'}(t_i)$ denotes the stress on the nut face and it is equal to the clamping force $F_c(t_i)$; D_1 and D_2 are inner and outer diameters of the annular contact surface, respectively; and μ_1 represents the frictional coefficient of the bearing surfaces.

Table 1 The basic parameters of the bolted joint

Parameter	Value	Remark
m	33.3 (g)	The mass of the nut
α, β	$\pi/6$ (rad)	The thread profile angle
μ, μ_1, μ_2	0.3, 0.4, 0.3	The friction coefficient
ρ, P_{scw}	2 (mm)	The thread pitch
d_2, D_1, D_2, r_t, r_b	14.7, 24, 14.7, 14.7, 24 (mm)	The diameter
E_1, E_2	117 (Pa)	Young's modulus
ν_1, ν_2	0.25	The Poisson ratio
κ	2	The dimensionless constant
k_{th}, k_s, k_{cyl}, k_{hd}	1.47, 1.46, 1.51, 1.53 ($10^6 N$/mm)	The spring rate
k_f, k_w, k_g	1.4, 1.38, 1.42 ($10^6 N$/mm)	The spring rate
T_{max}	72.126 (N.m)	The maximum amplitude of assembly torque
κ_1	0.0015	The constant coefficient
θ_{max}	40.1π (rad)	The maximum value of the nut rotation angle

Therefore, the total assembly torque at the transition stage is as follows:

$$\mathrm{T}(\mathrm{t_i}) = \mathrm{T_1}(\mathrm{t_i}) + \mathrm{T_2}(\mathrm{t_i}) \tag{2}$$

Correspondingly, for the bolted joint example used in section 3.1, its torque at this stage is as follows:

$$\begin{aligned}\mathrm{T}(\mathrm{t_i}) &= -369.2048 \times A(t_i) \times h' + 3.8617 + 347.6491 \\ &\quad \times A(t_i) \times h' - 3.6363 \\ &= -21.5557 \times A(t_i) \times h' + 0.2254 (N{\cdot}mm)\end{aligned}$$

3.3 The linearity stage

Once the connection is tightened, its components, such as the connecting parts, the bolt, the washer, or the gasket, start to deform elastically. As found out by researches on material mechanics, the axial bolt tensioning force is linear with the nut rotation angle at the linearity stage of bolt assembly [10]. By introducing stiffness coefficients of the gasket and washer, this relationship can be expressed as follows:

$$\Phi(t_i) = \frac{2 \times \pi}{P_{scw}} \times F_b(t_i) \times \left(\frac{1}{k_{th}} + \frac{1}{k_s} + \frac{1}{k_{cyl}} + \frac{1}{k_{hd}} + \frac{1}{k_f} + \frac{1}{k_w} + \frac{1}{k_g} \right)$$

where $\Phi(t_i)$ is the nut rotational angle; P_{scw} is the pitch of the thread; $F_b(t_i)$ is the axial tensioning force of the bolt; and k_{th}, k_s, k_{cyl}, k_{hd}, k_f, k_w, and k_g denote the spring rates of engaged threads, exposed threads, bolt body, bolt head, fastened plate, washer, and gasket, respectively, which can be approximated with domain knowledge or calculated [8].

Therefore, the assembly torque at linearity stage can be described as follows [16]:

$$T(\mathrm{t_i}) = \left(\frac{\rho}{2\pi} + \frac{\mu_2 \times r_t}{2 \times cos\beta} + \mu_1 \times r_b \right) \times F_b(t_i) \tag{3}$$

where ρ is the thread pitch, μ_2 is the frictional coefficient between male and female threads, r_t is an effective contacting radius between threads, β is the thread profile angle which is 30° according to UN and ISO standard, μ_1 is the frictional coefficient between the contacting surfaces of the nut and part, and r_b is an effective bearing radius of the bearing contact area under the nut.

Similarly, for the same bolted joint example, its torque at the transition stage can be calculated as follows:

$$\begin{aligned}T(t_i) &= \left(\frac{2}{2\pi} + \frac{0.3 \times 14.7}{2 \times 0.866} + 0.4 \times 24 \right) \times \frac{\Phi(t_i)}{0.868 \times 10^{-3}} \\ &= 14.4 \times \Phi(t_i)\ (N{\cdot}m)\end{aligned}$$

3.4 The yield stage

When the external force applied on the connecting parts exceeds their bearing limit, they will yield. This process cannot

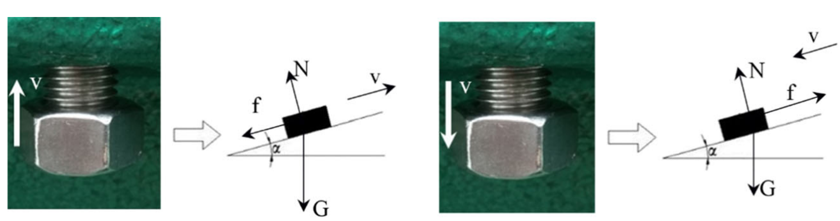


Fig. 3 The stress analysis of nut at the navigation stage

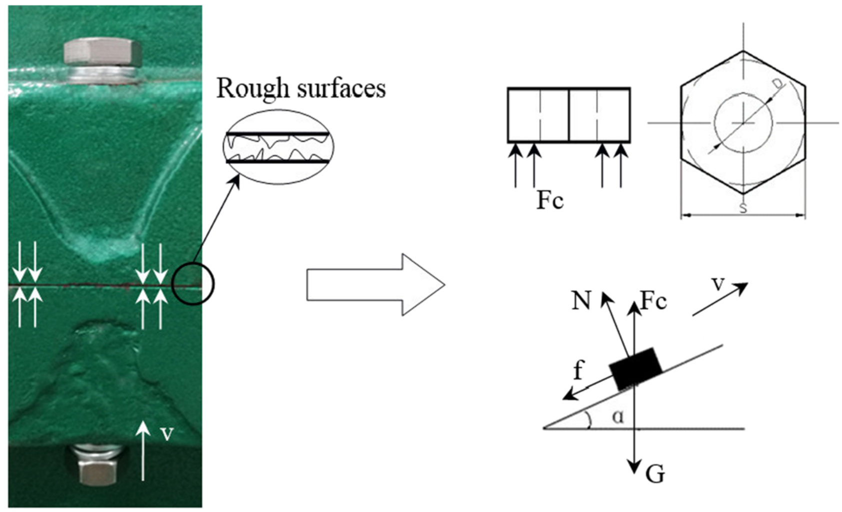


Fig. 4 Stress analysis of the nut at the transition stage

be described through a specific mathematical expression. Thus, in general, it is a common practice that the end of the bolted joint assembly is reached when turning the nut by another 90 degrees along the assembly direction after the assembly force reaches its preload value set. And this process is indeed the yield stage of the assembly. In this paper, a penalty function is used to simulate the variation of the assembly torque within the range of the final turning of the 90 degrees, and it is given as follows:

$$T(t_i) = T_{max} - \kappa_1 \times (\theta(t_i) - \theta_{max})^2 \quad (4)$$

where κ_1 is a constant coefficient, θ_{max} denotes the maximum value of the nut rotation angle, and T_{max} is the constant representing the maximum amplitude of assembly torque variation at the yield stage.

Correspondingly, for the bolted joint example, its torque at the transition stage is as follows:

$$T(t_i) = 72.126 - 0.0015 \times (\theta(t_i) - 40.1 \times \pi)^2 (N{\cdot}m)$$

4 Case studies

In order to verify the feasibility of haptic rendering approach based on the bolted joint assembly and evaluate the user performance of the VA operation, a prototype VA system is designed and developed. Two groups of experiments are carried out.

4.1 The VA prototype

The prototype VA system is shown in Fig. 5. The operator is able to complete the bolted joint assembly with haptic feedback using a 6 degree-of-freedom haptic device, which is a force feedback device developed by the authors [17] and the CyberGlove with 18 sensors. The prototype system runs on an Intel E3-1231 (3.4 GHz) PC with Windows 7 operating system, a NVIDIA GeForce GTX 750 Ti graphics card, and 8 GB of memory. The programming is done using C++ and Microsoft Visual Studio 2010 as the development environment.

4.2 Design of experiments

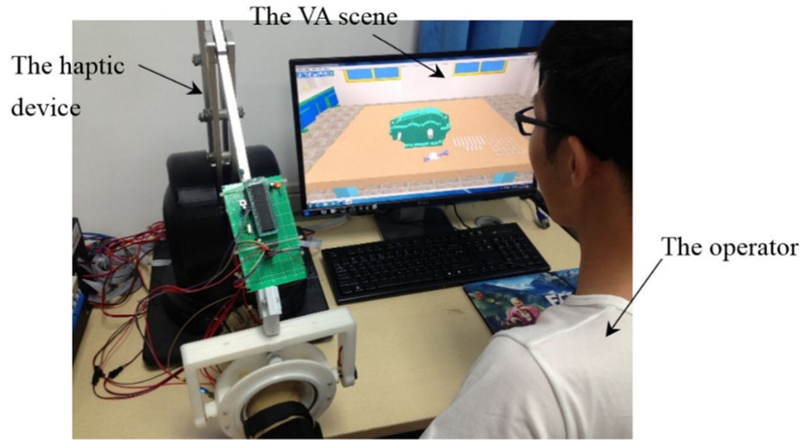
Gear reducers are widely used in industrial machines for speed and torque transmission. While bolted joints are applied to fasten its upper and lower casing together to provide a close-gearing transmission. In this work, a two-stage gear reducer, ZQ350, which contains 12 bolted joints, is used as the experimental object, and two groups of experiments were conducted. The first is a validation experiment, in which the assembly of 12 bolted joints on the reducer casing is conducted in the realistic and virtual environment, respectively, and a 3D force sensor is used to collect the assembly force during the realistic process, while the second group is a heuristic user performance experiment to evaluate the user performance during VA operations.

4.2.1 The validation experiments

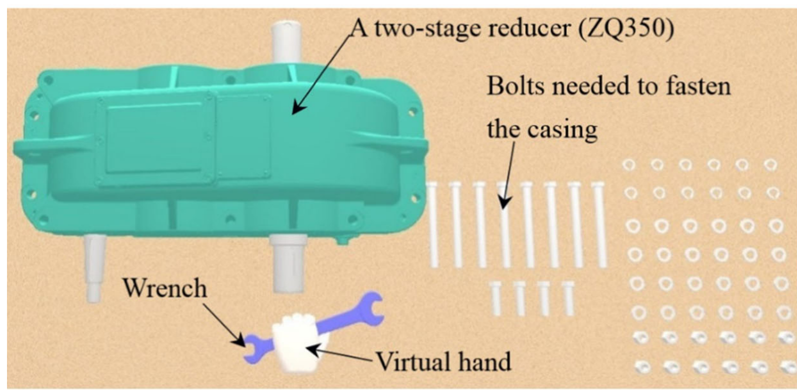
According to the design, there are two groups of bolts: M16×180 and M16×75 (unit: mm), respectively. Moreover, to better validate the haptic rendering approach with different materials, bolts with two types of materials, stainless steel and carbon steel, are adopted. Hence, there are two experiments with bolts of different materials. In order to keep the consistency of the operation, one unique operator conducts the assembly both in virtual and real environment.

In order to validate whether the force rendered is the same as that happened for actual assembly, an assembly force measurement system is set up to measure the actual force to

Fig. 5 Illustrations of the prototype VA system



(a) The overview of the VA prototype



(b) The closer view of the VA scene for a two-stage gear reducer

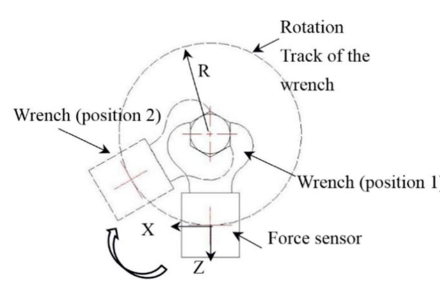
be compared. The system (Fig. 6a) consists of three parts: a laptop, an intelligent display instrument, and an open-end wrench. The laptop is responsible for receiving, displaying, and storing force data from the intelligent display instrument; which collects electrical sensor signals, then converts it to the corresponding digital ones shown by its four digital display channels, while the open-end wrench is modified to have a force sensor firmly attached onto it so that the operator's force acting on the wrench can be measured. Moreover, by changing the hand position on the arm of the open-end wrench, various assembly torques can be achieved. As shown in Fig. 6b, the force along X axis of the force sensor is always along its rotational speed direction while tightening of the nut. Thus, the assembly torque can be calculated by the product of the force in the X-direction and the wrench radius R.

During the experiment, as shown in Fig. 7, the male operator's left hand holds a common wrench to fix the bolt head and his right hand uses the modified wrench to tighten the nut. In order to reduce the error of the experimental data caused by the accidental collision between the wrench and other parts, this assembly operation is relatively careful and slow.

On the other hand, in VA environment, the force feedback is calculated according to the force rendering approach proposed in section 3, then scaled to the force output magnitude

Fig. 6 The assembly force measurement system

(a) The measuring system



(b) The illustration of wrench working

Fig. 7 Tightening the nut in realistic environment

of the haptic device, finally output to the operator through the haptic device. As shown in Fig. 8, the operator manipulates the virtual hand to grasp the virtual wrench and, then, tightens the nut one by one. During the process, a guiding force is designed to assist the operator to align the wrench with the nut. The value of the force feedback to the user is inversely proportional to the distance between the virtual wrench and the target position. This force pull the virtual wrench (together with the operator's hand) to the target assembly position. Moreover, the bolt is fixed by software during the assembly, so the operator just operates the haptic device to rotate the virtual wrench accordingly to fasten the nut. During this fastening process, the force is calculated by identifying the specific stage and then feedback to the operator.

4.2.2 The evaluation experiment of user performance in virtual environment

In order to evaluate the user performance during VA operations, a heuristic evaluation method evolving from Nielsen's heuristics [18, 19], which is widely used to find potential usability problem, is adopted. Specifically, 20 student evaluators were involved to experience the VA system. Among them, four are familiar with the field of VA and haptic technology, ten are major in mechanical engineering and have basic understanding about VA and haptic technology, and the rest six are from other disciplines. Moreover, before the experiments, each participant received an indispensable training about half an hour on the bolted joint assembly in virtual environment so as to get familiarized with VA and operating process. Then, they were asked to complete the specified experimental tasks in virtual environment. Finally, they needed to score on the evaluation factors of the VA system. The four evaluation factors are as follows:

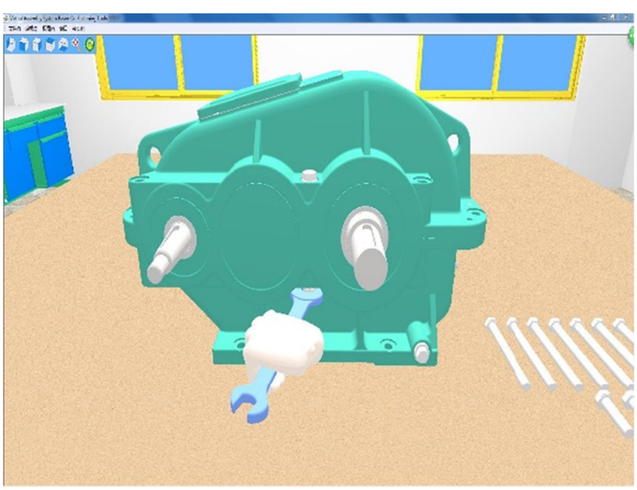


Fig. 8 An illustration of VA of bolted joints

1) Immersion of the VA operation: measure how much feeling of presence the user can perceive during the VA operation, and it is a comprehensive indicator.
2) Stability and continuity of haptic rendering: measure if the user could feel the haptic feedback stably and continuously.
3) Guiding ability of haptic rendering: measure if the haptic rendering could guide the user to complete the VA task.
4) Flexibility and efficiency of the VA operation: measure if the user could interactive with virtual environment flexibly and complete the VA task effectively.

The task for the evaluators is designed as following steps:

Step 1: This step is mainly to do some preparatory work for the experiment. An introduction to the VA system and basic operation skill will be taught to evaluators, such as includes the proper operation of haptic devices, the illustration of four evaluation factors, and so on.
Step 2: This step is the core part of the experiment. Each evaluator is required to complete the bolted joint assembly on the virtual reducer individually. More specifically, after guiding the virtual hand to the assembly position, the operator controls the virtual hand to tighten the 12 nuts with the virtual wrench.
Step 3: Evaluators who complete the assembly task are asked to give a score for the above four factors, respectively, and the score ranges from 0 to 10; the higher the score, the better the performance of the factor.

4.3 Discussions

4.3.1 The fidelity of haptic rendering

No matter whether the experiment is in a virtual or that in real environment, it often happens that the open-ended wrench may collide with other parts like the reducer casing and this may result in a sudden change of force data returned. To reduce such data errors, four groups of experimental data with less disturbance are selected and analyzed. As shown in Fig. 9a, since the assembly torques of the first two stages are much smaller than the latter two, in order to clearly observe the changes, four local sub-graphs corresponding to four stages are shown from Fig. 9 panels b to e, and the unit of the vertical axis used in Fig. 9b, c is changed to N.mm for a better readability.

In Fig. 9a, it can be seen that the virtual assembly torque calculated is generally consistent with the actual experimental data. While for different stages, only at navigation stage, the changing trend for assembly torque in actual environment is different from that in virtual environment. As shown in Fig. 9b, in actual environment, the value increases from 0 to maximum and then fluctuates within a small range. This is consistent with the operating process from startup to the final stable condition. While in virtual experimental environment, it is always a constant, since it is calculated by the theoretical model and it is 0 before the stage. As expected, at each stage, the experimental values always deviate from the theoretical values, which is more obvious for the carbon material.

In order to quantitatively analyze the numerical differences of the assembly torque between the experiments at all stages, two statistical values are calculated, one is the maximum relative error (MRE): $max\left\{\frac{\left|T_v^i-T_a^i\right|}{T_a^i}, i=1,2,3\ldots\right\}$, another is the mean absolute percent error (MAPE): $aver\left\{\frac{\left|T_v^i-T_a^i\right|}{T_a^i}, i=1,2,3\ldots\right\}$, where T_v^i and T_a^i are the assembly torque of bolts in virtual and actual environment. They are listed in Table 2.

As from Table 2, it can be found that for the first three stages, their error level is similar, the MRE is around 10%.

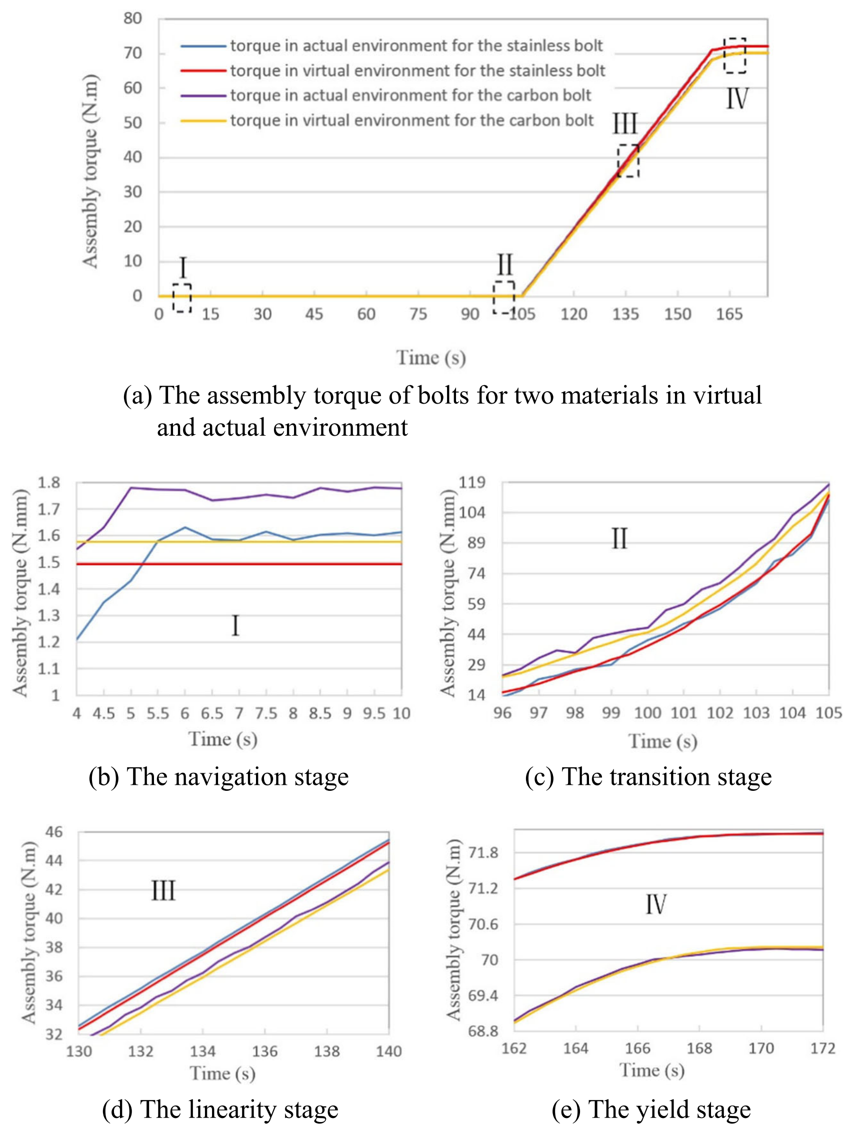


Fig. 9 The results of the validated experiment

Table 2 The MRE and MAPE of assembly torques for each stage

Assembly stage	Bolted joint of stainless steel		Bolted joint of carbon steel	
	MRE	MAPE	MRE	MAPE
Navigation	0.10592	0.06921	0.13432	0.09927
Transition	0.12523	0.05402	0.16812	0.08322
Linearity	0.11237	0.01481	0.11369	0.01819
Yield	0.00554	0.00221	0.00684	0.00324

MRE means "maximum relative error"; MAPE stands for "mean absolute percent error"

Only for yield stage, the error turns to be smaller. At this stage, the actual assembly torque reaches its biggest value range (around 70 N·m as shown in Fig. 9e), while the users are more careful to operate the wrench in order to get the final 90 degree's turning done, so both the MRE and MAPE are the smallest; in other words, the error state is ideal at this stage among all the four stages. For bolted joints of different materials, the actual assembly torque measured is close to that from the proposed approach by all means. However, an interesting finding is that the error measured for bolted joint of stainless steel is less than those for carbon steel bolts. After careful analysis and consulting the operator, it is found that the surface quality of the stainless steel bolt used in this experiment is better than that of carbon steel; therefore, during screwing, the friction felt by the operator with the carbon one is bigger. This causes the operator to exert more forces onto the wrench and, hence introduces error, such as some pressure force not in assembly direction, to the assembly toque.

4.3.2 The user performance of the virtual assembly system

Since the evaluators had a training session before the experiments and they all have basic understandings on virtual assembly, so they are asked to give scores on the four evaluation factors directly. The maximum, minimum, and average values of evaluators' scores are show in Table 3.

From Table 3, the scores of the four evaluation factors given by the evaluators range from 6 to 9, which indicates that the evaluators are satisfied with the performance of the VA system in general. Moreover, the average score of the first factor, namely the immersion of the VA operation, is as high as 8.263. And the reason could be the following: on the one hand, the rendering scene is built with reference to the actual assembly environment; hence, it is more realistic, while on the other hand, more specifically, for this work, there is haptic feedback to the users, which renders the force continuous and reliable. Similarly, the average score of the third evaluation factor, namely the guiding ability of haptic rendering, is 8.103, which should be owed to the accuracy of the haptic rendering approach and the application of a guiding force. The users' scores indicate that the haptic feedback can effectively assist the operator with the assembly task.

However, for the second evaluation factor, stability and continuity of haptic rendering, it gets a lower score of 6.684. After further communication with all evaluators and careful analysis, it is found that the accidental collision between the virtual wrench and other parts is quite common while the evaluator aligns the wrench with nut; this is due to the poor sight information, which directly results in a kind of sudden shock of the feedback force. In fact, this collision happens in the actual situation too, and it could be avoided once the user gets a better view. Other than factor 2, the average score of the flexibility and efficiency of the VA operation is relatively lower (7.514) and the scores are relatively concentrated. Since the adjustment of the evaluator's view is provided via the keyboard hotkeys, which is not as convenient as it is in reality. And most of the time, it is taken by looking for the right view during the assembly. So this decreases the flexibility and efficiency of the VA operation to some extent.

Other than focusing on the maximum, minimum, and average scores, the underlying distributions of the scores are statistically analyzed by their quartiles. As the box plot in Fig. 10 shows, the Q3 of the first and third evaluation factors are both above 8, which means most evaluators are OK with the immersion of the VA operation and guiding ability of

Table 3 Users' scores on the evaluation factors

No.	Evaluation factor	Min	Max	Average
1	Immersion of the VA operation	7	9	8.263
2	Stability and continuity of haptic rendering	6	9	6.684
3	Guiding ability of haptic rendering	7	9	8.103
4	Flexibility and efficiency of the VA operation	7	8	7.514

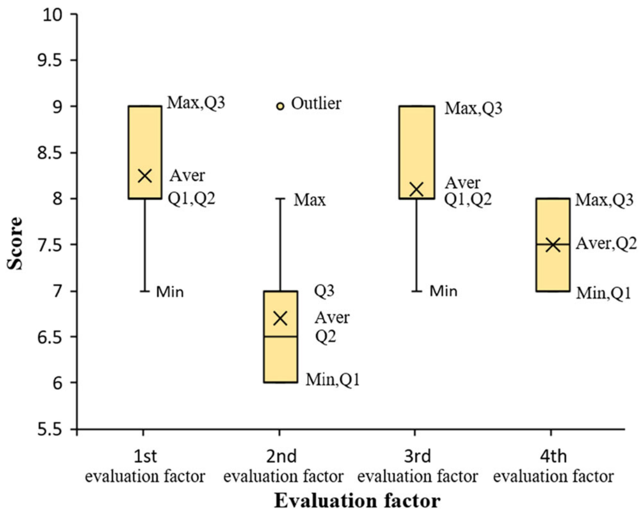


Fig. 10 Box plot of the users' scores on the evaluation factors

haptic rendering. The score of the last evaluation factor is relatively concentrated (between 7 and 8) and the Q2 is just half of the maximum and minimum. This shows that the overall evaluation of the flexibility and efficiency of the VA operation is good, and the evaluators can accept the interaction of view switching through keyboard. As the quartile for the second evaluation factor, its Q3 is below 7 and this is negative judgment for the stability and continuity of haptic rendering from the evaluators. In addition, there is an outlier of the second evaluation factor and its score is up to 9. After further analysis, it is found that the evaluator is very careful and slow while performing assembly task, thus avoiding unnecessary collisions.

5 Conclusion

This work proposed a staged haptic rendering approach for VA of bolted joints. The force feedback is calculated based on consecutive stages, namely navigation stage, transition stage, linearity stage, and yield stage. Moreover, the proposed approach is implemented and validated by conducting two groups of experiments on a two-stage gear reducer, ZQ350, in reality as well as in the developed prototype VA system. The results of the first experiment validate that the actual assembly torques measured are consistent with those from the proposed approach, while the second experiment involves evaluators to conduct VA in the prototype. Their scores have shown that the haptic rendering approach performs well in general, and more specifically on improving the immersion feeling of the VA operation and guiding ability of haptic rendering. However, actual assembly conditions may vary. With different assembly direction and tools, the force condition changes. Therefore, a more comprehensive study is needed to apply and adjust the proposed approach for more assembly cases.

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