Haptics of Screwing and Unscrewing for Its Application in Smart Factories for Disassembly

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Abstract. Reconstruction of the skilled human sensations and design of related control system is important for robust control of the robots. We are developing an unscrewing robot with a comprehensive control system for the automated disassembly of electronic devices. Experiments involve screwing and unscrewing, and since humans typically have a broad range of screwing experiences and sensations throughout their lives, we conducted a series of experiments to find out these haptic patterns. Results show that people apply axial force to the screws to avoid screwdriver slippage (cam-outs), which is one of the key problems during screwing and unscrewing, and this axial force is proportional to the torque which is required for screwing. We have found that type of the screw head influences the amount of axial force applied. Using this knowledge an unscrewing robot for the smart disassembly factory RecyBot is being developed, and experiments confirm the optimality of the strategy used by humans. Finally, a methodology for robust unscrewing algorithm design is presented as a generalization of the findings. It can speed up the development of the screwing and unscrewing robots and tools.

Keywords: Haptics · Screwing · Automated disassembly

1 Introduction

The importance of e-waste recycling is rapidly increasing due to the need for energy conservation material resources, and landfill capacity. For example, Apple corporation recently developed a disassembly line for iPhone 6 [9] with a high material recovery potential. A Skoltech-MIT project RecyBot has the goal to develop a universal high-speed intelligent robotic system for electronics recycling. RecyBot consists of several robots, each tailored to perform a specific task, whose joined target is to disassemble smart-phones at the component level and enable material recovery. Previous attempts of mobile phone disassembly automation have been primarily focused on the disassembly system design [6,7], yet are outdated due to the changes in a typical phone from 2006 to 2017, which obstruct

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milling and recent advantages in computer vision techniques, which potentially bring system autonomy issues to a new level [12]. Therefore, RecyBot focuses on the development of the series of smart robots with computer vision to automate operations often performed during electronic waste disassembly. The unscrewing operation is an essential part of the RecyBot project because screws are a central category of fasteners and are found in the majority of electronic products [11]. Screw removal has to be performed via non-destructive means, since it often precedes the battery removal, which, if broken, may cause more environmental damage, than the ecological benefits of recycling. The previous attempt to build an unscrewing robot was described by Chen et al. [4], who built a robot to assist humans in electric vehicle batteries disassembly. The paper focuses on the tool change procedure, and it omits the details of the unscrewing itself. An extensive analysis and detection of common errors during automatic unscrewing are done by Apley et al. [2]. They use a screwdriver, attached to a DC motor with a potentiometer to read the screwdriver head rotation angle, and continuously estimate the torque from the motor current. They successfully detect normal unscrewing, cam-out (slippage between the screwdriver and the screw), the situation, when the screwdriver missed the screw, and the situation, when their system cannot provide enough torque. However, they do not suggest how to overcome these problems.

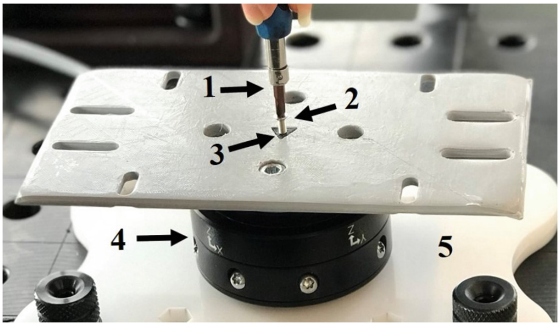


Fig. 1. The experimental setup. The disposable plastic prism (2) with a 3 mm hole for the M3 screw is fixed inside the prism holder (3). The prism holder is attached to a 6 DOF force and torque sensor (4), which is fixed to a heavy table using an acrylic fixture (5). The screw is unscrewed by a participant with a corresponding screwdriver (1). The center line of the screw is positioned along the Z-axis, which points up. Force and torque along Z-axis are recorded with the frequency of 100 Hz.

The cam-out is an important issue during osteosynthesis procedures in medicine. Majewicz et al. built a simulator to teach surgeons to screw using the torque data gathered by an automated screwdriver, and validated the teaching with the help of more experienced surgeons [8]. The cam-out in the same medical context was studied in [3], where screws were intentionally damaged, and this damaging torque was measured, but the paper does not describe a way to prevent slippage which occurs not from metal deformations, but from the screwdriver coming out of the screw.

It is assumed that screwing and unscrewing patterns of humans, who incorporate their broad experiences in the patterns which they use, may lead us to insights into robotic screwing and unscrewing. Two critical characteristics of the process have been measured: force applied along the screwdriver and screwing/ unscrewing torque. Then it is observed how humans prevent cam-out (screwdriver slippage), which is one of the most common failures [2], and how they decide, when to stop. This paper presents a methodology for robust robotic unscrewing development to decrease the cam-out occurrence, using skilled humans data. The experiment on human screwing and unscrewing is presented in Sect. 2 and a description of the application of its results to an unscrewing robot is given in Sect. 3. First, experimental setup and procedure are described in Sect. 2.1, where it is measured how humans perform screwing and unscrewing operations in different conditions. The conclusions from the human experiment are presented in Sect. 2.2.

In the second part, an unscrewing robot is described, and the results of the first part are applied. First, mechanical design is described in Sect. 3.1, then the control system, which is inspired by the experiment from the first part, is elaborated on in Sect. 3.2. The experiments with the robot are further described in Sect. 3.3. The overall approach is discussed and summarized in Sect. 4.

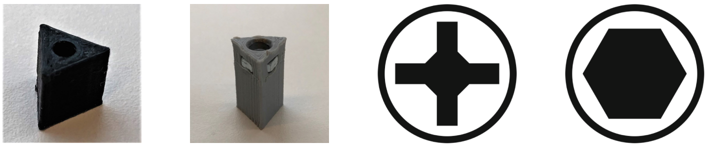
2 Human Experiment

The principal approach of this paper is to design robot control algorithms based on the coefficients which are obtained from humans. Screwing and unscrewing are rather complex procedures, and humans integrate their past experiences into their behavior and pattern. Human screwing and unscrewing are classified, their important characteristics are measured, and then these parameters are transferred to robotic unscrewing. The experiment is designed to get a thorough and broad view of the patterns human use.

2.1 Experimental Design

The principal factors to measure and control in the screwing and unscrewing operation are the force and the torque which are applied perpendicular to the direction of the surface and along the axis of the screw (axial force). However, the torque applied during the interaction with the real smart-phone screws was too low to measure with the available sensors. To measure the human patterns of screwing and unscrewing, an experimental setup has been built as shown in Fig. 1. A plastic holder (3) was designed to keep the pilot holes and nuts object, where the screwing process happened. The object, where the participants screwed and unscrewed, was designed as a disposable triangular prism (2) with a pilot hole in the center of it of 3 mm diameter. These prisms were fixed in the center of the holder and replaced after being used. To reproduce the presence of a nut in some smart-phones, an M3 nut was added to some prisms during the 3D printing 5 mm below the end of the prism. During all the experiment were used M3 x 8 mm screws with two different heads: Phillips and internal Hex, with their corresponding screwdriver (1). The Phillips head was chosen, because it was observed that the 65.4% of the screws present in a set of 6 smart-phones of different brands are of this type. The Internal Hex head was chosen because his application is different than the Phillips type. In the Fig. 2 both the disposable plastic prisms and the heads of the two different screws used during the experiment are shown.

The holder was attached to a Robotiq 6 DOF force and torque sensor FT300 (4) and the pilot hole in the prism was aligned with a sensor along Z-axis. This sensor was chosen because of its frequency of 100 Hz for data output and the low noise signal of 0.1 N and 0.003 N $\cdot$ m in F_z and in M_z respectively [1], that allowed getting enough data for the purposes of this experiment. The sensor was fixed to a massive and stiff table (Siegmund Professional S4 welding table) using an acrylic base (5).



(a) Disposable plastic prism with a 3 mm pilot hole.

(b) Disposable plastic prism with an M3 nut added during the 3D printing.

(c) Phillips screw head

(d) Internal Hex screw head, also called Allen screw

Fig. 2. Disposable plastic prisms, where the participants screw and unscrew. Two types of screws were used, Phillips and Internal Hex.

Ten participants, who used screwdrivers at least occasionally for their duties, were recruited for the experiment, seven men, and three women, in an age range from 22 to 40 years. They were asked to screw the screw in the prism, holding the screwdriver only with one hand during all the process, and, if it was necessary, to hold the screw with the other hand. After that, they were asked to unscrew the same screw. The experiment consisted of 9 screwing and 9 unscrewing operations in 6 different conditions as shown in the Table 1. The condition is called "exceptional" when a screwdriver was used that did not correspond with the screw (Phillips 2), and the others" are called "typical" conditions. The disposable prism has been replaced after each unscrewing, to avoid the influence of the thread, which appeared in the plastic. Four of the participants were also asked to screw and unscrew the screw into the disposable plastic prism without applying any force in the direction of the screw.

Table 1. The experiment conditions imposed on the subjects.

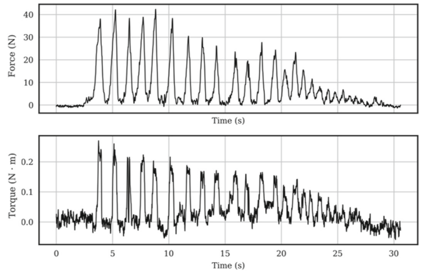
Repetitions	Operation	Screw type	Orientation of the screwdriver	Prism type	Screwdriver type
2	Screwing	Phillips	Horizontal	Pilot hole	Phillips 0
2	Unscrewing	Phillips	Horizontal	Pilot hole	Phillips 0
1	Screwing	Internal Hex	Horizontal	Pilot hole	Internal Hex 2.5
1	Unscrewing	Internal Hex	Horizontal	Pilot hole	Internal Hex 2.5
3	Screwing	Phillips	Horizontal	With M3 nut	Phillips 0
3	Unscrewing	Phillips	Horizontal	With M3 nut	Phillips 0
1	Screwing	Phillips	Horizontal	Pilot hole	Phillips 2
1	Unscrewing	Phillips	Horizontal	Pilot hole	Phillips 2
1	Screwing	Phillips	Vertical	Pilot hole	Phillips 0
1	Unscrewing	Phillips	Vertical	Pilot hole	Phillips 0
1	Screwing	Internal Hex	Vertical	Pilot hole	Internal Hex 2.5
1	Unscrewing	Internal Hex	Vertical	Pilot hole	Internal Hex 2.5

2.2 Experimental Results

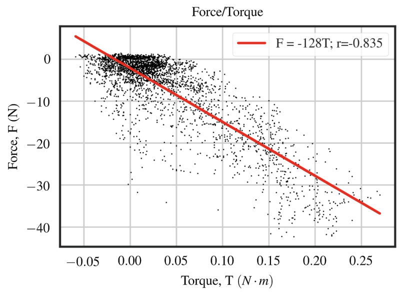
The typical patterns of force and torque during unscrewing of Phillips screws in plastic disposable prism are shown in Fig. 3. The oscillatory pattern with the frequency of (1.3 ± 0.4) Hz is observed in every operation plot. The average period of oscillations was calculated for all experiments using periods between local maximums. The deviation of max and min length of cycle from the average is used as an amendment. It is observed in all the measurements from all the participants both in torque and in force and is independent of age or gender. It is caused by the need for humans to regrasp the screwdriver due to lack of joints with limitless rotation.

The pattern of local maximums of torque and force represents the moments when real screwing and unscrewing were happening. The torque required to rotate the screw is defined by the friction, which is defined by the environment: it depends on the state of the thread in the plastic and weakly depends on the rotation speed in a wide range of speeds (see Sect. 3.3). During unscrewing from a disposable plastic prism (see Fig. 3a), the maximal torque is applied at the beginning of the procedure, and then it decreases gradually, which is defined by the decrease of the length of the screw inside the plastic and thus the friction decrease. In Fig. 3c a typical screwing pattern is shown. The torque is gradually increasing in the first seconds while the screw is dipping into the plastic. Then it remains constant indicating, that most friction is occurring due to the need to cut a new treading in the plastic. Final torque increase indicates the reach of the plastic surface with a screw head. Humans feel the torque increase and stop screwing.

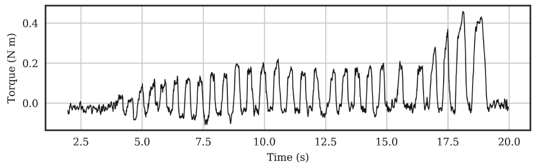
A correlation between force and torque applied simultaneously is observed, which can be seen in Fig. 3b. For all of the measured conditions the absolute value of the correlation coefficient $r = (0.75 \pm 0.13)$, which indicates a significant rela-



(a) Typical pattern of absolute values of force along the screw axis and torque during unscrewing of a Phillips screw from a disposable plastic prism.



(b) Relationship between force and torque for the time series from (a). Points represent individual measurements and the red line is the least squares approximation.



(c) Typical pattern of absolute values of torque during screwing of a Phillips screw into a disposable plastic prism.

Fig. 3. Typical patterns of force along the screw axis and torque during screwing and unscrewing an M3 Phillips screw in the disposable plastic prism.

tion. We than denote the Force/Torque ratio γ and take it as a characteristic of the screwing or unscrewing procedure in the specific conditions. Two reasons to apply force simultaneously with torque are, first, the need to avoid screw slippage and, second, the nature of human arm, which uses muscles to produce torque via forces [10]. To estimate the importance of the first factor, we compare the Phillips screws and screws with internal Hex. The average γ for screwing the Phillips screw operations is $\gamma = (106 \pm 37)\ \mathrm{m}^{-1}$ which is significantly higher than $\gamma = (57 \pm 25)\ \mathrm{m}^{-1}$ for screwing of the screws with internal Hex. Since the second factor does not depend on the screw, the difference is contributed to only by the slippage avoidance. Thus, the screws with internal hex are less affected by slippage, than the Phillips screws, being screwed or unscrewed with the same force.

In Fig. 4, a typical pattern of screwing a screw in the nut is shown. During the first seconds the torque is hardly distinguishable from noise, but when the screw head touches the surface, the torque increases, human feel it and stop screwing. The typical unscrewing pattern is very similar, but inverted in time and requires smaller maximum torque, than the maximum torque which was applied during screwing.

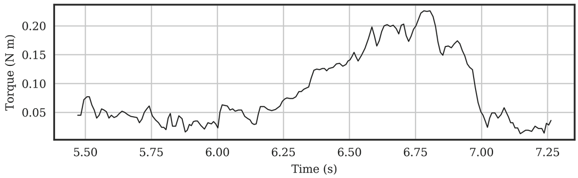


Fig. 4. Typical pattern of absolute values of torque during screwing of a Phillips screw into a disposable plastic prism with a nut. The black line represents the measurements.

In Fig. 5 a box plot of the γ coefficient is shown for all the typical conditions. The γ for the exceptional condition when the screwdriver does not match the screw is much larger, in the order of 300 ± 250 m^{-1} and was omitted to keep the scale sensible. The large γ is reasonable, since it was very hard for the participants to apply any significant torque, because of continuous slippage. Moreover, during operations of participants, when explicitly asked not to apply any force, and only apply torque, the slippage was also constantly occurring. This confirms the hypothesis, that the function of the typically applied force is to avoid slippage. The mean values of γ differ between screwing and unscrewing. For the taken conditions γ is typically in the range from 25 to 140.

The difference between horizontal and vertical operations could be introduced with the need to press the screwdriver in the screw in the horizontal position even during regrasp, to avoid its fall and caused by the relative comfort of force application in different orientations.

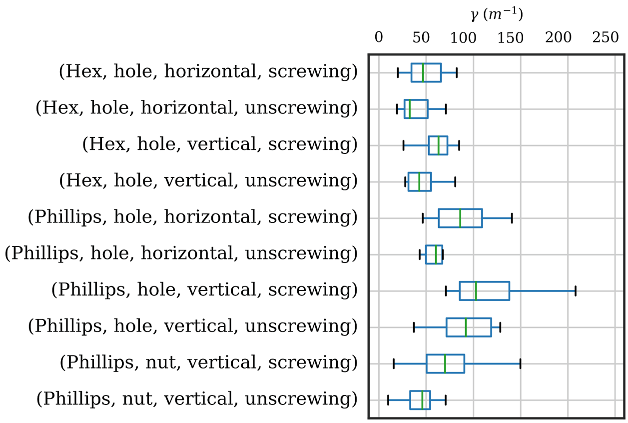


Fig. 5. Bar plot of Force/Torque ratio γ (m^{-1}) in different conditions. The conditions in the brackets represent (the screw type, "hole" is for the disposable plastic prism and "nut" is for a prism with a nut, the orientation of the screw, screwing or unscrewing).

We analyze the results of our user experiment using one-way ANOVA without replications, in order to see if the differences between conditions are real or due to chance. The chosen significance level is set to $p < 0.05$. According to the test findings, the Participant and Sex conditions have significance value p = 0.909 and p = 0.104 respectively, which are above 0.05, therefore we could conclude that this two conditions do not have any effect for the screwing and unscrewing processes: Force/Torque ratio didn't significantly change over experiments. Type of screw (hexagonal/Phillips) ($p = 5.3 \times 10^{-8} < 0.05$), prism type (pilot hole/M3 nut) ($p = 9.0 \times 10^{-11} < 0.05$), orientation of the screwdriver (horizontal/vertical) ($p = 1.5 \times 10^{-4} < 0.05$), operation (screwing/unscrewing) ($p = 4.7 \times 10^{-2} < 0.05$), and the physical condition of the users (physical performance, if they have a particular training or not) ($p = 7.1 \times 10^{-17} < 0.05$) are important parameters for screwing and unscrewing processes.

2.3 Discussion

The discovery of the linear relationship between applied torque and force is a key to designing a robust screwing or unscrewing system. Since the target torque is defined by the environment (see Sect. 3.3), the robust algorithm should use force control and define the force from torque, using the coefficient, obtained from humans for the exact conditions.

3 Unscrewing Robot

An unscrewing robot is being developed as a part of the RecyBot project. It is equipped with computer vision to detect screws and a gripper to unscrew them. To perform unscrewing well, the force applied to the screw has to be controlled. Analyzing data from human experiment helps to define appropriate pattern and thresholds for force and torque in robotic implementation. Maximum force, maximum torque, and force-torque relation are the important parameters that are used. The setup diagram is shown in Fig. 6.

3.1 Mechanical Design

A collaborative robot UR3 from Universal Robots was used to move the gripper. The design of the gripper, endowed with passive compliance, was done with the objective to increase the force feedback precision in the compliant direction of Z-axis [5]. The passive compliance is implemented by a linear bearing, a spring system, and a linear potentiometer. The relative position of the potentiometer indicates the force applied to the screw as defined by the spring system. The design of the gripper is shown in Fig. 7. The linear potentiometer was calibrated using a Robotiq 6 DOF force and torque sensor FT150 to allow the force measurement. The screwdriver in the gripper is attached to a brushed DC motor from Maxon, the current from which is measured and used to determine the torque applied during the operation in regular mode, but is ignored during this

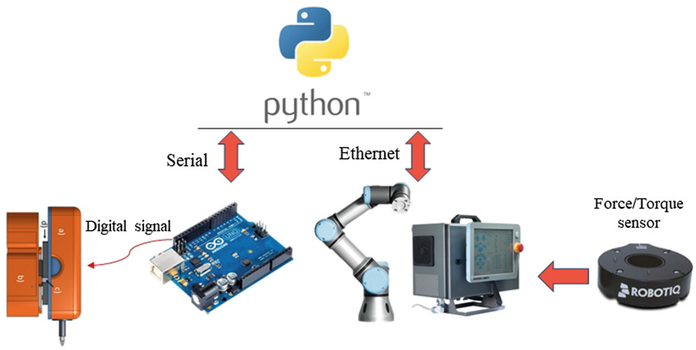


Fig. 6. The general scheme of communication in the testbed for robotic unscrewing.

experiment. Both force and torque could be measured by the internal gripper sources, and used in the real unscrewing. For the propose described in this paper, the force and torque feedback applied from the gripper was obtained by the same 6 DOF Robotiq sensor used in the Human Experiment in Sect. 2.

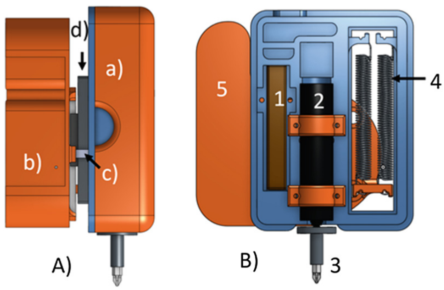


Fig. 7. The Gripper design used in the Unscrewing Robot. The lateral view A shows the cover of the gripper (a), the connection with the UR (b), the connection with the linear potentiometer (c), and the linear bearing. The internal parts of the gripper are shown in the front view B, the linear potentiometer (1), the motor (2), the screw driver (3), the spring system (4) and the connection with the UR (5)

3.2 Screwing and Unscrewing with Slippage Avoidance

Unscrewing procedure is controlled using a force control algorithm. The PID force controller with feed-forward signal was designed, and in Fig. 8 the structure of the control system is shown. The control output signal is a position command which is applied to the robot end-effector. The force feedback is received from the 6 DOF sensor.

In addition, to prevent cam-out, which is one of the most common failures [2], the force is applied according to the torque multiplied by the Force/Torque ratio γ, which is obtained from human experiment data. When the robot senses the slippage of the screwdriver (with a sharp drop in torque, see Fig. 9), the force is increased to prevent it. In fact, when the force, which is applied during the unscrewing is controlled, one can make the robot's activity closer to human activity as a clever actor.

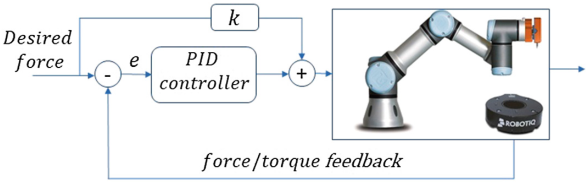


Fig. 8. Structure of the control scheme. Position is controlled using the force feedback.

3.3 Robot Screwing and Unscrewing Results

The robot was programmed with an algorithm, close to the proposed. The difference is in cam-out detection and increase of the force as a response. In Fig. 9 the obtained force and torque are shown. The cam-outs are clearly visible as drops in the torque. Their detection was implemented using a threshold. The force was being gradually increased, with higher increase speed, when slippage was detected. The frequency of the cam-outs notably drops with the increase of the force from 5 to 25 s. This means sufficiently large force has been reached to avoid cam-outs. The head of the screw touched the plastic at 40 s. The torque started to grow rapidly. When the Force/Torque ratio γ lowered due to the increase in torque, the slippage started to occur again after 43 s. Then the thread is overturned since no torque limit has been implemented in the prototype algorithm.

To check the hypothesis that the torque does not depend on the speed of the screw rotation, one experiment has been performed with the robot. The unscrewing speed was changed in a range from 22.5 to 360 degrees per second and the measured unscrewing torque in the same conditions was $T = (0.19 \pm 0.03)$ N$\cdot$ m. This confirms the hypothesis of the independence of the friction on the speed.

3.4 Discussion

The novel end-effector has been designed, which is able to screw or unscrew the screws with precise force feedback. The main feature of the robot is the desired Force/Torque relationship γ of the robot unscrewing, which is gathered from the human experiments. The results of the robotic unscrewing agree with the results of the human experiments and demonstrate the universality of the conditions of the successful unscrewing found in the previous part. The human experiment data helps us to find out the well-performing desired force pattern.

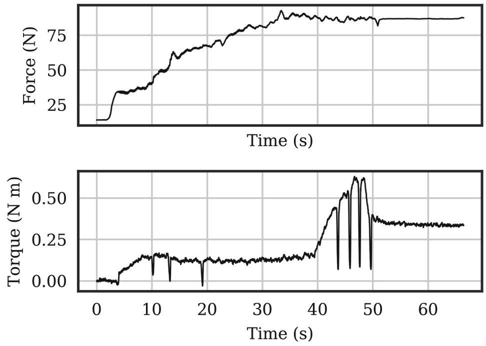


Fig. 9. Force and torque values obtained from a robot, screwing thew screw into a disposable plastic prism. The robot is set to gradually increase the force until the maximum value is reached. Cam-outs correspond to sharp drops in torque. Their frequency is decreasing from 5 s to 22 s when the force reaches the value twice higher than the one, computed from γ, the Force/Torque ratio in humans.

4 Discussion and Conclusions

A typical frequency of human screwing and unscrewing is reported here to be (1.3 ± 0.4) Hz without any dependence on age and gender. It seems to correlate more with the strength of the participants, but we did not measure this variable directly. A significant correlation between applied torque and force during screwing and unscrewing is discovered in this paper, and it should be a reasonable assumption for any screwing and unscrewing procedures design.

In this paper, a new approach for robotic screwing and unscrewing procedure has been proposed. To choose the constants for the robot screwing and unscrewing algorithm, one has to, first, measure the Force/Torque ratio γ humans typically apply in the exact conditions, and then implement the force control, based on the continually measured torque and obtained γ. One can increase the coefficient to introduce a safe margin but should consider the fragility of the environment. Also, the maximum torque humans use has to be chosen as a threshold for screwing condition detection. The γ depends on the type of the screw, and is higher for Phillips screws, which are more prone to cam-outs than internal Hex screws.

This methodology can speed up the development of the screwing and unscrewing robots and tools. For example, it can help in direct transfer of the haptic knowledge from the more knowledgeable experts to the novices in the simulators for surgeons and other professionals, where a required γ can be measured and taught. Likewise, in the RecyBot project it can reduce the slippage and increase the unscrewing process efficiency.

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