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A Survey of Automated Threaded Fastening

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***Abstract*— Threaded fasteners are prevalent throughout modern manufacturing. Thus, as the demand for automation in manufacturing increases, so does the demand for automated threaded fastening systems. However, many fundamental issues and engineering challenges still hinder robustness in automation, particularly for smaller screws and critical product finishing requirements. This paper surveys the state of the art in threaded fastening automation and discusses open questions for further research. This survey covers the following areas: 1) fundamentals of threaded fastening, including basic concepts and definitions; 2) analysis of the entire assembly process (consisting of part feeding and orientation, pickup, alignment, and driving), including discussions of tools, control strategies, and other considerations; 3) failure modes and techniques to mitigate them; 4) threaded fastening systems and electromechanical approaches; and 5) open challenges and suggestions for future development. Understanding the current state of automation in threaded fastening will provide a foundation for researchers to advance this field.**

***Note to Practitioners*—This paper is motivated by the problem of an automated assembly of small screws, one of the most challenging problems in a smartphone assembly. It represents a rigorous review of robotic screwdriving literature to identify the state-of-the-art and open problems. The review material was targeted toward engineers working on related problems with the sponsor and has proved useful to them. To benefit researchers in the field of robotic and automated assembly, we have compiled the review material in the form of a survey paper. This paper covers theoretical fundamentals, tools, control and failure detection strategies, industrial applications, and open problems for robotic screwdriving. It provides a foundation for readers to familiarize themselves with the state of the art and conduct further research on this thread.**

***Index Terms*—Automated assembly, fault detection, robotics, screws, threaded fasteners.**

I. Introduction

THREADED fastening is one of the most prevalent assembly methods in manufacturing [1]. This method is often used when future disassembly is required for maintenance or rework [2]. Moreover, screws are the only fasteners that provide continuously variable joint tension by adjusting the tightening torque, which adds to their versatility [1]. In the late 1970s, Nevins and Whitney [3], [4] found that threaded fastening is constituted 27% of typical assembly tasks over a range of common products and second only to peg-in-hole assembly at 33%. In 1995, a survey of 24 product lines is classified 37.9% of all mechanical assembly operations as screw and bolt insertions [5]. Given its ubiquity, threaded fastening is an attractive target for automation.

Unfortunately, threaded fastening is one of the most difficult assembly methods to fully automate [2]. Threaded fastening is deceptively complicated relative to its ubiquity [6]. The complex interactions between the internal and external threads during the initial insertion period make analysis difficult [2], [7], [8]. Several fault conditions, such as cross threading [6], appear sporadically and can cause catastrophic failures [9]. For example, in 1979, a cross-threaded pipe has caused the experimental well Ixtoc I [10] to blow out near the coast of the Mexico's Yucatan Peninsula, causing one of the most disastrous oil spills (140 million gallons) of all time [11]. In order to enhance the robustness of automated threaded fastening systems and control the chance of failure, system designers must understand the screwdriving process, its failure modes, and the strategies available to mitigate them.

In this paper, we survey the state of threaded fastening automation. We begin by presenting the fundamentals of threaded fastening in Section II. Then, we give an overview of the entire assembly procedure, first discussing screw feeding and orienting, pickup, alignment, and insertion in Section III and then focusing on the screwdriving process in Section IV. Possible failure modes and detection techniques are covered in Section V. In Section VI, we discuss the existing automated threaded fastening systems and techniques. In Section VII, we consider open challenges for robotic screwdriving and promising future directions. By outlining the current state of the field, we provide a foundation for researchers to advance both the theory of screwdriving and new systems for its automation.

II. Fundamentals

The following description is briefly drawn from [14]–[16]. Some of the terms are shown in Fig. 1.

A. Thread Concepts and Terminology

There are two types of external threaded fasteners: *screws* and *bolts* [12]. A *bolt* is intended for use with a nut or a threaded hole to create a high clamping force, while a *screw* is intended for use with a preformed internal thread (*machine screws*) but may also form its own thread (*self-tapping screws*). The terms *bolts* and *screws* are often used interchangeably.

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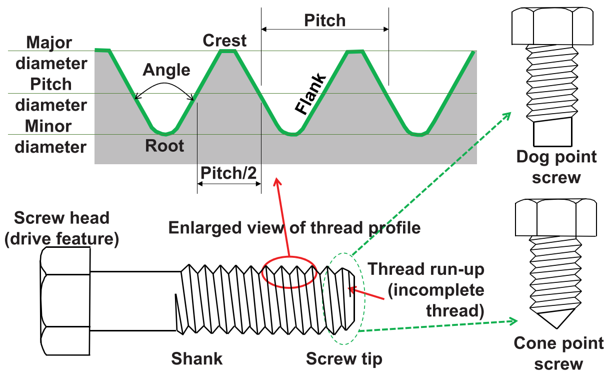

Fig. 1. Screw, its thread profile, and typical tips (adapted from [12] and [13]).

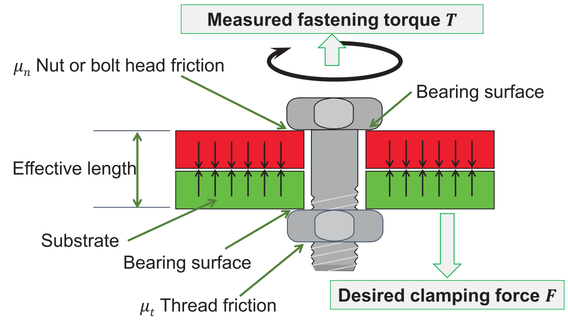

Fig. 2. Bolted joint.

A *thread* is a helical ridge of uniform cross section on the external or internal surface of a cylinder. *External threads* occur on bolts, studs, or screws; *internal threads* occur on nuts and tapped holes. The *thread profile* or *thread form* is the configuration of the thread in the axial plane. The top and bottom of the thread are the *crests* and *roots*, respectively. They are connected by the *flanks*. The *flank angle* (called *half-angle* for symmetric threads), which in most cases is 30°, is the angle between a flank and the perpendicular thread axis, i.e., half of the angle shown in Fig. 1.

On an external thread, the *major diameter* is measured between the crests, and the *minor diameter* is measured between the roots. On an internal thread, the roles are reversed: the major diameter is at the roots and the minor diameter is at the crests. The profile is often rounded off or flattened at the roots and crests. The *pitch diameter* is the diameter of a theoretical cylinder that passes through the threads and splits the distance between the crests and roots in half.

The *lead* is the axial advance of a screw during a complete turn, while *pitch* is the axial distance between the adjacent threads. Often, *lead* and *pitch* are equal when the thread has only one winding—a *single-start* thread. For *multiple-start* screws, such as those often found on jar lids, the lead is equal to the pitch times the number of starts. Threads can also be classified by a thread size: a *coarse thread* has a larger pitch and thread form than a *fine thread*. Different thread sizes are appropriate in different circumstances; however, for automated assembly, coarse threads are often preferred [16], since they reduce the rate of cross threading and jamming (see in the following) [8].

The notion of *thread fit* defines a qualitative measure of tightness between mating fasteners derived from the allowance and tolerances [16]. *Allowance* is the amount by which the internal thread diameter exceeds the mating external thread diameter, and the *allowance ratio* expresses allowance as a fraction of the internal thread major diameter [2]. A *clearance* fit has a nonzero allowance to ease mating while allowing some play, while an *interference fit* has a negative allowance (positive interference), thus requiring special tools for the initial rundown of the screw [16]. The *length of thread engagement* is defined as the axial distance over which the fully formed internal and external threads are in contact in the mated configuration. It is one of the key fastener strength aspects and one which the designer can control.

Last, we turn to the anatomy of a screw. As shown in Fig. 1, the *screw head* is the section with the largest diameter. It contains a load surface for providing axial clamping force as well as a drive feature to transmit torque. The *shank*, the cylindrical portion from the bottom of the head to the tip, can be fully or partially threaded. In the *screw tip* region, threads are incomplete, that is, they undergo a gradual *thread run-up*. The form and length of the run-up is important in avoiding cross threading (see Fig. 7) [8]. In order to assist insertion, the screw tip may be chamfered (Fig. 8) or equipped with other styles, such as dog-point or cone-point tips (Fig. 1) [13].

B. Bolted Joints

Threaded fasteners apply a specified *preload*, or joining force, between two parts. This preload generates a clamping load between the parts and keeps the bolted joint (see Fig. 2) together during its service life, whether the service cycle is in tensile or shear loading [12]. Therefore, in order to understand how best to use threaded fasteners, we must understand how to predict and measure this clamping load.

Unfortunately, measuring the clamping force F (see Fig. 2) directly requires advanced instrumentation, such as a torque–tension research head [14], [17] or a strain-gauge-based sensor [18]. In practice, assemblers measure the applied torque T (see Fig. 2) and derive the clamping force analytically using the elastic torque–tension relationship

$$T = KDF \tag{1}$$

in which T is the applied torque, D is the major diameter (nominal bolt diameter), F is the clamping force, and K is the *nut factor*, which can be found in published tables (see [14]). This equation applies during the linear elastic zone of the torque-angle tightening curve (Fig. 6). This equation does not consider the prevailing torque, which is the torque required to overcome the interference between the threads (e.g., plastic inserts to prevent loosening) without contributing to bolt stretch. Hundreds of factors affect the tension in a bolt when the tightening torque is applied [17], so the torque-angle curve is typically determined empirically.

The *joint rate*, or *torque rate*, is defined as the increase in torque with angular displacement while advancing a fastener in the ISO-5393 standard [19]. It affects the final clamp load

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TABLE I
CLASSIFICATION OF BOLTED ASSEMBLY SYSTEMS (MODIFIED FROM [15] AND [20])

Category	Examples	Requirements	Control Strategies
Class-A (safety-related): the failure can affect user safety	Wheels, brakes	Assure that all screws are tightened and all joints are correct to trace errors and store results. 100% guarantee.	Torque-angle control or yield control
Class-B (reliability-related): the failure can only affect machine functions	Gear box fixture, engine fixture	Assure that all screws are tightened and all joints are correct.	Torque-angle control
Class-C (standard): the failure does not affect the machine functions	Sun roof, plastic protection	Assure a correct torque. Assure that all screws are tightened to correct torque.	Torque control

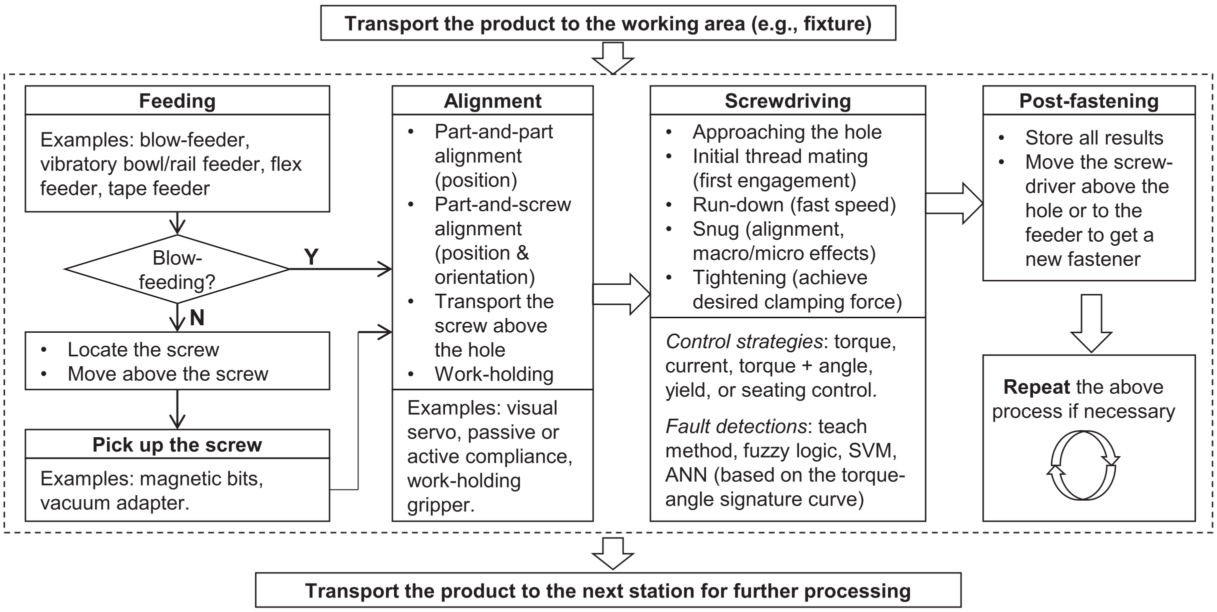

Fig. 3. Typical screw fastening procedure in an automatic assembly line.

achieved by a given torque. Based on the torque rate, bolted joints can be classified into *hard* and *soft* joints. Hard joints have 30° or less rotation between snug (see Fig. 6) and final torque (or 27° between 10% and 100% torque), while soft joints have 720° rotation between snug and final torque (or 650° between 10% and 100% torque).

As shown in Table I, bolted joint assembly systems can be classified into three categories: class-A (safety-related), class-B (reliability-related), and class-C (standard). This classification is commonly used in automotive production [15], [20]. Table I also shows typical examples, specific requirements, and commonly used control strategies for each category. Note that a bolted joint can become loose due to factors such as creep or relaxation in the threads or external load [17]. In the case of vibration-induced loosening, loosening is initiated when complete thread slip has occurred prior to head slip, which was previously considered the initial point of loosening [1]. In the sequel, we will cover assembly procedure, control strategies, fault detection, and automation systems that are required to produce reliable bolted joint assemblies.

III. OVERVIEW OF THE ASSEMBLY PROCEDURE

Automated screw fastening involves multiple stages of operation, often including feeding, alignment, screwdriving, and postfastening [21]. Fig. 3 shows a representative procedure in an automatic assembly line. First, the parts to assemble are transported to the working area and fixed in place. Second, the screw is prepared for driving using a screw feeder and a pickup tool. Third, after aligning the part to be bolted with the fixtured part, the screw is moved above the hole and aligned. Fourth, the screw is driven into the hole (see Section IV for details) and the system is reset for the next part. An overview of tools and strategies used in assembly is as follows.

A. Screw Feeding and Orienting

Since threaded fasteners are often supplied in bags or boxes, they must be organized and oriented uniformly before being fed to the screwdriver, a task typically performed by *screw feeders*. Fig. 4 presents some common feeding mechanisms: vibratory feeders, flex feeder [22], tape feeders [23], shaker trays, and blow feeders. Different feeder types are appropriate depending on the type of screws, their materials and sizes, system cost, and speed requirements.

"The vibratory bowl feeder is the most versatile of all hopper feeding devices for small engineering parts" [24]. An electromagnet induces vibration in the bowl, causing the screws to climb up the helical track and orient themselves correctly at the outlet. Rail feeders work similarly. However, both feeders, which are complex to adjust, only work when the *aspect ratio* (screw length divided by screw head diameter) is

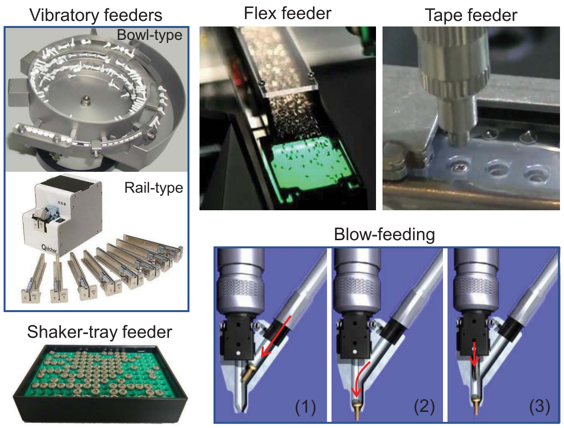

Fig. 4. Examples of screw feeders [22], [23].

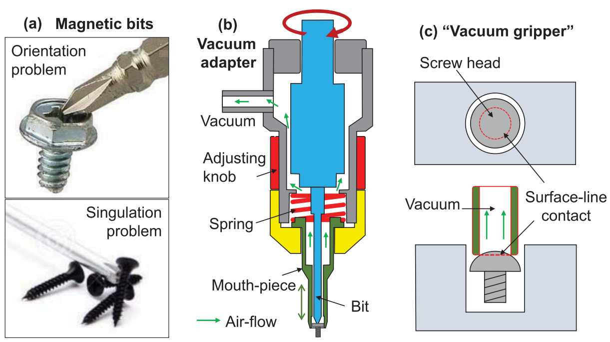

Fig. 5. Screw pickup. (a) Magnetic bits. (b) Vacuum adapter. (c) Vacuum gripper designed for recessed locations [27].

greater than a certain threshold (generally, 1.3) [22]. Vibratory feeders also have issues of heat generation and electromagnetic interference [25]. Alternate excitation methods, such as piezos [25], are also available and work better for ferrous screws [26].

B. Pickup Strategies

A better feeding method is blow feeding (Fig. 4), in which screws are blown through a tube after orienting (often by a bowl feeder) and sent directly to the screwdriver tip. This method eliminates the time-consuming screw pickup step and thus improves throughput. Like vibratory feeding, blow feeding has a minimum required aspect ratio, since screws with small aspect ratios tumble in the tube. In addition, the blast of air may carry contaminants to the work area. Specially designed blow-feeding equipment is required for clean room applications, such as hard drive assembly [28].

When blow feeding is not used, the screw must be grasped using an alternate strategy, such as magnetic attraction, vacuum suction, or mechanical grasping [22]. These strategies must be able to grasp a screw, maintain the grasp during transit, and release the screw after the operation is complete. Each method is appropriate in different circumstances.

Magnetizing the tip of the driver bit provides a simple way to pick up screws, but it has several disadvantages. Magnetized bits require ferrous screws. Also, as shown in Fig. 5(a),

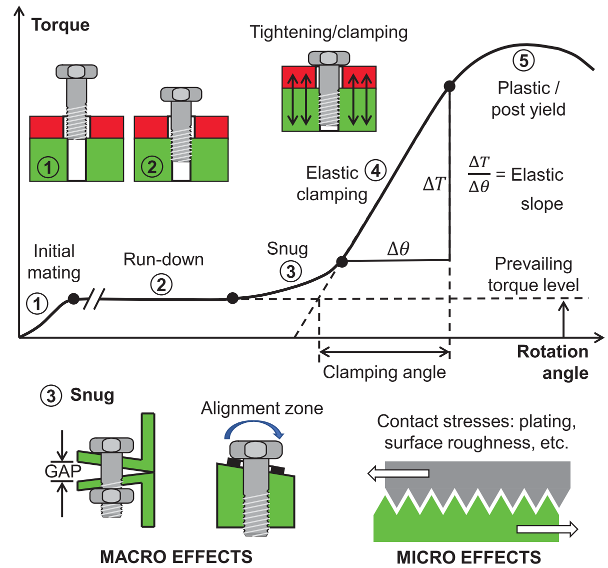

Fig. 6. Torque versus angle curve during the screwdriving process [15], [16].

magnetized bits can have orientation and singulation problems, which must be avoided in the automated operation.

Vacuum grippers provide good orientation control and work across a variety of materials, and thus are usually preferred for automated screwdriving [26]. This method requires accessories, such as a vacuum pump, valve, tube, and vacuum adapter. As shown in Fig. 5(b), the spring in the adapter allows the mouthpiece and screw to travel axially, allowing the screw to engage its mating threads and the bit to engage the screw head. One problem with vacuum pickup is that the bulky size [22] and large footprint of the vacuum adapter make operating in cluttered spaces difficult. Alternate designs of the vacuum gripper can mitigate the clutter problem in some scenarios, such as the design shown in Fig. 5(c) [27].

C. Alignment

After acquisition, the screw must be aligned with the parts that it will join. Both the alignment between the fixtured part and the assembled part (part–part alignment) and between the fixtured part and the screw (part–screw alignment to avoid failures [29]) are necessary for successful screwdriving. Fixtures, compliance devices, such as remote center of compliance (RCC) [6], [30], and visual servoing techniques [31] can assist in alignment, as validated by several studies [30], [32]–[34]. Vision also helps in localizing fasteners and target holes in unstructured environment [35]. During alignment and the subsequent screwdriving operation, grasping devices are often used for workholding [33], [34].

IV. Screwdriving Process

Once the screw has been picked up and properly aligned, screwdriving can begin. The driving operation can be divided into several stages. One way to visualize the process is by plotting applied torque against the total rotation angle to produce the *torque-angle curve*; a typical curve appears in Fig. 6. The first stage corresponds to the initial mating of the bolt thread to the nut thread, also known as *starting the thread* [6], [36] or *finding the thread* [37]. The second zone is the *prevailing torque zone* (or *rundown zone*), in which the screw is driven steadily through the hole until the screw head makes contact with the work surface. The third zone is the *snug zone* (or *alignment zone*), during which the fastener and joint mating surfaces are drawn into alignment. The nonlinear snug zone is a complex combination of macroeffects due to the mating parts being drawn together and microeffects due to surface/thread deformations, as shown in Fig. 6 [17]. The fourth zone is the *elastic clamping zone*, in which the slope of the torque-angle curve is constant. For some safety-critical applications (e.g., car brakes), the screw must be tightened past the elastic clamping zone to the *postyield zone*, during which plastic deformation occurs. By understanding the mechanics and failure modes of the above process, successful screwdriving can be ensured.

Another way to understand the screwdriving process is by considering the energy transfer, since the area under the torque-angle curve is proportional to the energy required to tighten the screw [15]. To calculate the fastening torque, the detailed version of (1) may be used [12]

$$\begin{aligned} T &= KDF \\ &= \left(\frac{p}{2\pi D} + \frac{\mu_t r_t}{D\cos\alpha} + \frac{\mu_n r_n}{D}\right) DF \qquad (2)\\ &= (K_1 + K_2 + K_3)DF \qquad (3)\end{aligned}$$

where p is the thread pitch, α is the thread angle, μ_t and μ_n are the friction coefficients of the thread and the nut, respectively, r_t is the effective radius of the internal thread, and r_n is the equivalent diameter of the friction torque between the clamping surfaces. r_n can be calculated as

$$r_n = \frac{1}{3}\left(\frac{r_o^3 - r_i^3}{r_o^2 - r_i^2}\right) \qquad (4)$$

where r_o and r_i are the outer and inner radii of the clamping surface patch [38]. In (3), the geometric factor K_1, the thread friction factor K_2, and the underhead friction factor K_3 correspond to the fractions of torque needed to stretch the bolt, overcome the thread friction, and overcome the friction between the clamping surfaces, respectively. Typically, only 10% of the energy is used to stretch the bolt, while the other energy is used to overcome friction [17].

The overall screwdriving operation can be divided into three major subprocesses [6], [37]: *initial thread mating*, *rundown*, and *tightening* with some variations or additional steps when considering self-tapping screws (see Section IV-D).

A. Initial Thread Mating

The initial thread mating is critical, as the most common errors, such as cross threading and jamming (Fig. 7), occur during this stage [8]. Improper mating can deform the thread and damage the fastener permanently. Thus, mating the threads accurately is essential for successful screwdriving.

One common failure during thread mating is *angular cross threading* (often called "*cross threading*" for short when there is no ambiguity), "in which the first (full) external thread crosses the internal thread in such a way that the thread engaged on one side of the internal thread is not on the same revolution as the thread engaged in the opposite side" [2], [8] (Fig. 7; also see Fig. 12, case 3). To avoid this, the first full external thread must not be allowed to cross under the crest of the internal thread, as shown in Fig. 7. To prevent this condition, the angular misalignment between the screw and the mating hole must be less than the *cross-thread angle*, which is defined as

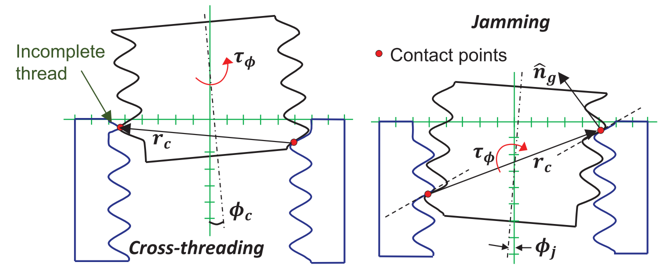

Fig. 7. Cross-threading angle and jamming angle [8].

$$\phi_c = \arctan\left(\frac{p}{2}, |r_c|\right) > \frac{p}{2(1-a)d} \qquad (5)$$

where p is the pitch, d is the internal thread major diameter, a is the allowance ratio (ad is the actual allowance), and r_c is the vector between the contact points shown in Fig. 7 [8]. Some references [6], [13] use an alternate value, $\phi_c = \arctan(p/d)$, which is about twice of the above value, as a rough approximation. The first value is preferred, because the threads might be damaged already when using the latter one.

A variety of techniques, from control strategies to mechanical compliance to customized trajectories, help combat angular cross threading. One control strategy is to maintain very stiff control of the tilt angle if $\phi < \phi_c$ and softer control outside this region [8]. Mechanically using an RCC can reduce the incidence of cross threading, as shown in Fig. 8(a) [6]. One explicit mating trajectory is the *back-spin first* method, in which the fastener is first rotated backward until it drops slightly, which indicates that the starting point for the two threads has lined up. The screw is then turned back an additional amount (e.g., 45°) before driving commences. This method is slow and requires sensing, but it works well with fasteners with large diameters and small pitches (i.e., small θ_c), where very small angular errors could cause angular cross threading [13], [39], [40].

Parallel cross threading is a more subtle form of cross threading [6]; it occurs when the thread run-up of the two parts is twisted together during initial mating [36], [42]. Unlike angular cross threading, parallel cross threading can occur even without angular misalignment. In fact, this failure is induced by excessive screw rotation speed for a given insertion force [36]. Most screwdrivers work at a low speed during initial mating [37], so parallel cross threading is unlikely to occur [6]. If the error persists, the back-spin method [13] and linear axial compliance [6] can also help to counteract it.

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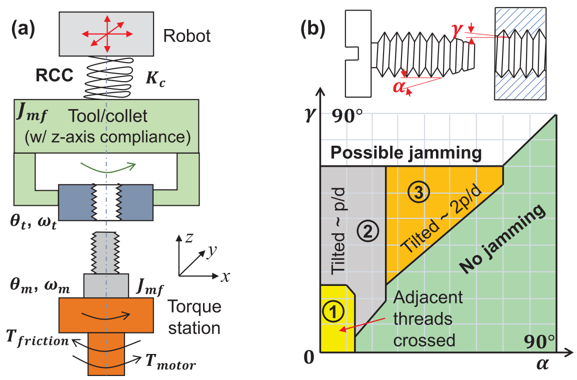

Fig. 8. Mitigating cross threading. (a) Passive compliance [6]. (b) Chamfered fasteners investigated in [13] and [41].

Another failure mode of screw mating is jamming (see Fig. 7), which is similar to jamming in the peg-in-hole assembly [43]. Jamming can occur under high stiffness control of tilt angle if the initial tilt angle is greater than the jamming angle [8]. For standard fasteners, the jamming angle is three or four times smaller than ϕ_c in (5). Reducing the control stiffness can reduce friction and thus prevent jamming. This is similar to the manual operation experience that jamming is easy to avoid if using a light touch [39].

A variety of mechanical and software techniques exist to assist the thread mating. Visual servoing has been used in [31]. Another method to assist the starting of screws is to change the tip shape, e.g., using "dog point" and "cone point" screws, as shown in Fig. 1. This method has disadvantages—extra cost and extra length—but the advantages are considerable, as discussed in [13]. Romanov [41] investigated chamfered fasteners through a geometric approach without considering friction. As shown in Fig. 8(b), the chamfer angles for the bolt and hole are α and γ, respectively. He concluded that α should be greater than γ to avoid cross threading and jamming.

B. Rundown

After the initial thread mating, the screw is run down until the screw head touches the part. Since the chance of error is low, this operation may be performed quickly [37]; the primary concern is how to detect when to stop and if any failure (e.g., cross threading) has occurred. Typically, those conditions are detected by monitoring the driving torque (the rundown resistance is dominated by thread friction and axial insertion force) while measuring the driven angle using an encoder. In one instance [29], researchers estimated the insertion length by measuring the vibrations in the force/torque profile during screwdriving (see Fig. 9). Typically, angle measurement via encoder is sufficient to detect the successful entry into the tightening phase.

C. Tightening

During tightening, the screw is torqued against the threads to achieve the desired clamping load. The process must be monitored to ensure that the clamping load is achieved and no failures have occurred. The monitoring strategies fall into

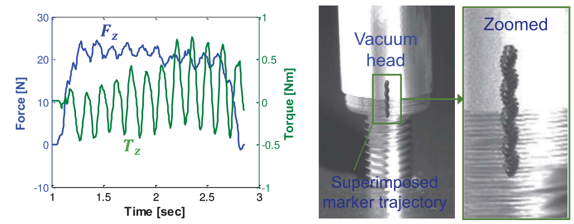

Fig. 9. Rundown operation. (a) Measured force and torque signals. (b) Screwdriver tip trajectory captured by the high-speed camera [29].

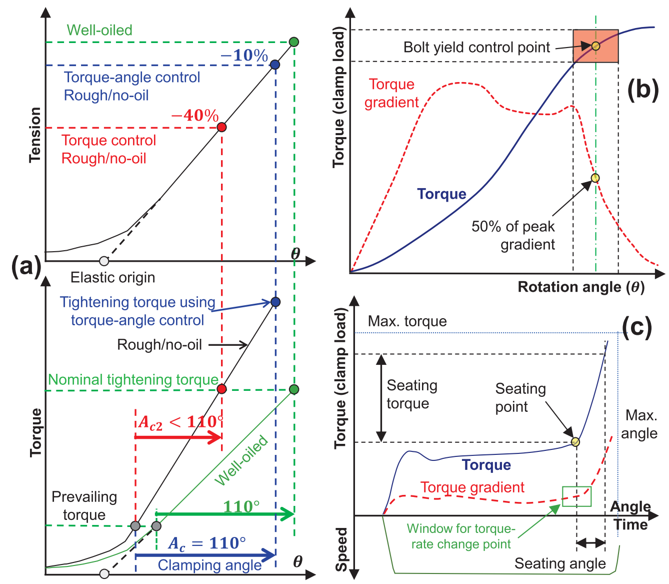

Fig. 10. Screw tightening strategies. (a) Torque-only control versus torque-angle control [17]. (b) Yield control [45]. (c) Seating control [37].

three broad categories [15], [20], [44]: torque-only control, torque-angle monitoring and control, and torque-rate control.

1) Torque-Only Control: This approach controls/monitors only the driving torque and assumes known torsional stiffnesses for the associated interfaces. However, in this method, the clamping force is difficult to observe and, hence, control; it might deviate by as much as 50% due to frictional variations or other unmodeled parameters [20]. For example, as shown in Fig. 10(a), compared with the baseline well-oiled case (low friction), the tension created for the rough/no oil (high friction) case through torque-only control (with the same tightening torque) is reduced by 40%. In this case, as shown in Fig. 10(a), the clamping angle A_{c2} is much smaller than the desired value A_c [17]. While torque-only control is easy to implement, its low robustness against uncertainties makes it a poor choice for applications with high precision requirements.

2) Torque-Angle Monitoring and Control: For joints where safety and reliability are dependent on proper tension, both the torque and the rotation angle must be monitored and controlled during tightening. This torque-angle control strategy can be further divided into two cases: 1) torque control with angle monitoring, for which the performance in repeatability and accuracy is similar to torque-only control (however, this method can detect the variation of friction, and can be used

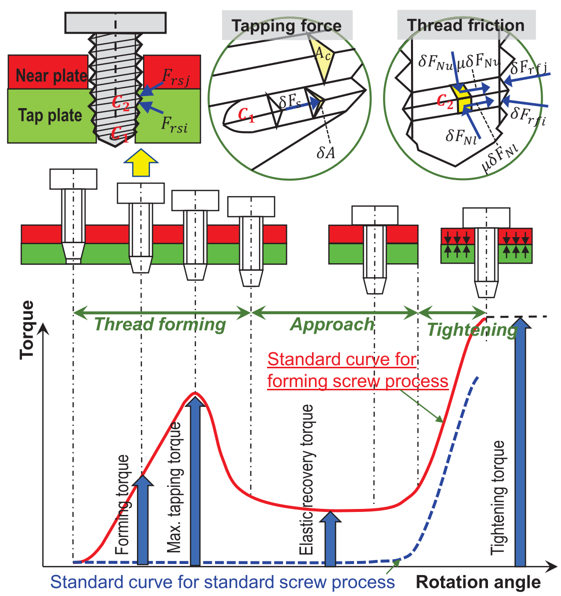

Fig. 11. Torque-angle curve of thread-forming screw insertion process [47]. Top: tapping force and thread friction [48].

for fault detection [20]) and 2) angle control with torque monitoring, which can reduce the scatter in tension to ±15% [20]. As suggested in Fig. 10(a) [17], by stopping the screwdriver at a specified angle after the trigger torque is attained, the scatter in tension is reduced to 10%. A key element in the torque-angle control is the *elastic origin*, which is located by projecting the torque-angle curve to the zero torque or prevailing the torque level [17]. In the elastic tightening zone, the clamp load is proportional to the angle of turn (i.e., the clamping angle A_c in Fig. 6) measured relative to the elastic origin [17].

3) Torque-Rate Control: This strategy involves measuring the driving torque, turn angle, and torque gradient. Examples of torque-rate control include yield control, shown in Fig. 10(b) [45], and seating control, shown in Fig. 10(c) [37]. In the yield control, in which the fastener is torqued to the *postyield zone* by monitoring the torque gradient, the bolt tension directly depends on mechanical characteristics. Hence, this method has a better performance in accuracy and repeatability than the torque-angle control. Moreover, it achieves very high tension within the safety limits and is often used for safety-critical assembly such as wheel brakes and hydraulic pumps. In the seating control, the gradient of the torque with respect to angle is monitored in order to detect the *seating point*, where the screw head touches the joint surface. Then, the same seating torque or seating angle is applied to all joints even though the joints may vary, thereby eliminating floating screws [37]. This method is ideal for joints where the screws are cutting or forming their own threads (see Section IV-D); however, the tools are expensive [46].

D. Self-Tapping Screws

Another important type of screw is the self-tapping screw, which instead of being inserted into a prethreaded hole forms the threads as it is inserted. Although the initial insertion does not require thread alignment, subsequent insertions may strip the threads [2]. Thus, self-tapping screws are used for assemblies that rarely need disassembly [2]. There are two basic types: thread forming and thread cutting.

1) Thread-Forming Screws: Thread-forming screws form the internal threads by displacing (without cutting) the material, thus creating a zero-clearance fit. Thread-forming screws are used more and more often, particularly in the automobile industry [47], because they provide large *binding forces* to prevent loosening, even under vibration.

Most research on form tapping is based on experimental studies and mechanical models for load calculation. In 1972, Hayama [49] analyzed thread-forming screws and established a model using the minimal energy method. Seneviratne *et al.* [48] developed a quasi-static model (confirmed by experiments) of the self-tapping screw insertion process. They also studied parameter identification [50] and fault detection for automated assembly line [51], [52]. Stéphan *et al.* [47] conducted an experimental study on the forming and tightening processes for thread-forming screws.

The insertion process for thread-forming screws can be divided into three stages: thread forming, screw advancement, and tightening, as shown in Fig. 11. Maximum tapping torque occurs when the tapered part breaks through the lower end of the hole. The driving torque decreases to an elastic recovery torque in the second phase after all the threads have been formed. The driving torque in the third phase includes the elastic recovery torque and the tightening torque [47].

2) Thread-Cutting Screws: Thread-cutting screws have cutting edges and chip cavities that create a mating thread by cutting the material they are driven into. The cutting action reduces the driving torque. Essentially, the screwdriving profile of thread cutting screws follows a torque-angle curve similar to thread-forming screws but with lower driving torques [47].

E. Mathematical Modeling

Dunne [6] developed piecewise linear and nonlinear dynamic models for the torque control of a threaded part assembly; the schematic is shown in Fig. 8(a). Based on these models, he investigated different torque control strategies. However, the detailed interactions between the male and female threads, which are unique to threaded fasteners, are not modeled.

Nicolson [2] analyzed the configuration space (C-space) for threaded insertion, which has no simple description except in the special case of peglike [53] contact. The reason is that the screw geometry does not allow a simple reduction from 3-D to 2-D space, because the thread-starting points on the bolt and nut must coincide for correct insertion. He used equations to describe the C-space and developed simplified thread models for stiffness control. His results could not predict contact states for reasonably large positioning errors [54].

Wiedmann and Sturges [55] modeled the thread mating problem as a group of parametric equations and created a tessellated solid model to study contact points. They also developed a detailed geometry model to determine the contact states for the initial thread mating phase [54]. These models

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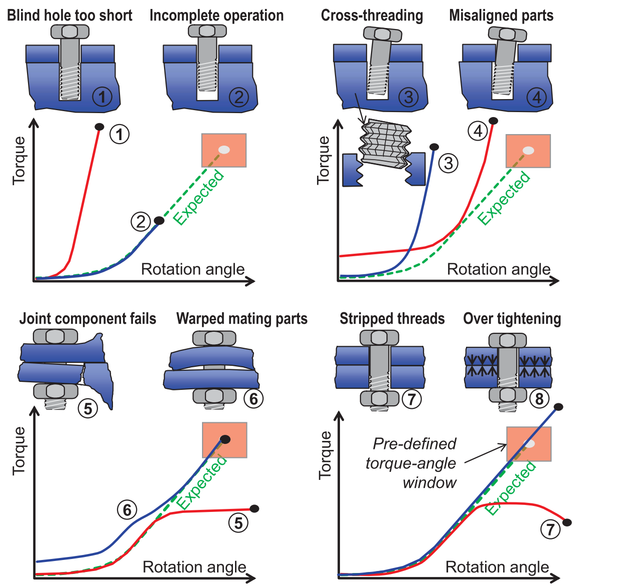


Fig. 12. Typical torque-angle curves for various failures (modified from [45]).

can be applied to visualize contact conditions which could lead to different failures and to the design of active control algorithms or passive compliance mechanisms to correct alignment errors.

V. Quality Monitoring and Fault Detection

Robust autonomous screwdriving systems require reliable fault detection and recovery. Even well-engineered systems can be tripped up by part tolerance issues, bad material, insufficient lubrication, improper tightening strategies, or tool wear. Fig. 12 shows some typical fault cases [45] for screwdriving; failure modes for self-tapping screws can be found in [51], [52], and [56]. Failures can also occur during screw acquisition and alignment, as discussed in Section III. In automation, reliable fault detection and isolation, which can provide information needed for error recovery operations, is required for improved quality and productivity [57].

Many fault detection algorithms and monitoring strategies have been developed for the screw insertion process. One of the most commonly used methods is the *teach method* [46], which often involves limit checking [37]. This method assumes that a particular screw insertion process will have a unique torque-angle *fastening signature* curve, while faults typically show up as major deviations from normal signals (see Fig. 12). Thus, as a setup procedure prior to assembly, the signature signal corresponding to the particular screwdriving operation is taught and stored, using the average of correct insertion examples [51]. During assembly, this method compares the real-time insertion signals with the stored correct signature signals. As shown in Fig. 12, a screw insertion is considered successful if its *fastening signature* curve follows the taught trajectory and stops within the predefined torque-angle window (limit checking). The standard teach method can be improved upon in a variety of ways [46], including the *torque-rate approach* (an example of *trend checking* [58]), which requires correct fastening signatures to fall within the predefined torque-rate windows [46]. While the teach method and its variants are simple to implement and generally reliable, they generally require lengthy setup times, because the insertion signature has to be taught for each new production procedure [52]. In addition, this method is inflexible and impossible to generalize to different equipment and setups, and, thus, it is mainly restricted to high volume or high unit cost production [51].

To overcome the limitations of the commonly used teach method with limit checking, fault diagnosis strategies through artificial intelligence, soft computing, and model-based fault detection have been developed [58], [59]. The model-based approach is flexible, but it requires an analytic model of the screw insertion and accurate knowledge of system parameters [50], [52]. Higher fidelity process models, which could improve the performance of model-based methods [57], are still limited in the literature, as discussed in Section IV.

Conventional modeling methods often face difficulties when dealing with changing and noisy process conditions with limited data available [57]. Computational intelligence methods, such as artificial neural networks (ANNs) and fuzzy systems, offer ways to cope with these problems. For example, ANNs have been used to monitor the thread-forming process [60], machine screw insertion [29], and self-tapping screw insertion [51], [52], [56], [61], [62]. Fuzzy control and clustering methods have been studied for screw insertion [63], bolt/nut tightening [64], and thread forming [60]. Other methods, such as support vector machines [29], have also been investigated.

Most methods mentioned earlier can achieve around 90% or better (e.g., 97% in [29]) performance in a recognition rate of different failure modes. However, there is still a lot of room for improvement before deployment to the actual assembly line, for which a much higher standard is required. Currently, there is no benchmark to compare the performance of different algorithms, because the performance actually depends on the specific applications and tuning parameters. Moreover, these advanced methods are complicated, thereby creating barriers that prevent many engineers from adopting them to the actual assembly line. Consequently, the *teach method* is still the most commonly used method by threaded fastening suppliers [37], [45] for real applications. In addition, many algorithms in the literature only cover limited failure cases; the actual production line is more complicated. Thus, a systematic framework [57] that can take advantage of different algorithms for quality monitoring and fault detection is required.

From systems engineering and fault diagnosis perspective, the framework shown in Fig. 13 provides a systematic way to construct a fault detection system for the entire threaded fastening process. In this framework, different monitoring strategies and fault detection methods can be combined in order to achieve the improved performance. The first task is to use expert knowledge and failure mode and effect analysis [59] to find significant symptoms that are robust against noise, disturbances, and uncertainties. The second task is to define needed measurements based on the identified symptoms. A model-based approach can help to reduce physical sensors (to reduce cost) and still maintain high process information levels. Common symptoms (e.g., model residuals and

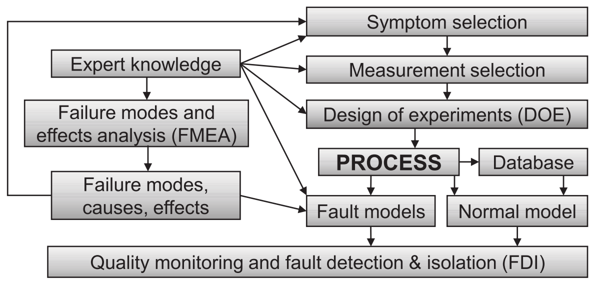


Fig. 13. General quality monitoring and fault detection framework [57].

fault frequency) and measurement methods (e.g., vibration, force, and vision) for screwdriving fault detection can be found in [57]. Experiments are then designed to collect statistically significant data from the process which can be used to create a model bank consisting of normal condition model and multiple fault models. The normal model is trained using collected data and is sensitive to abnormal changes. Then, reliable quality monitoring and fault detection can be achieved using model-based algorithms as implemented in [58] and [59].

Fault detection alone provides only a go or no-go type signal. An intelligent system must take an appropriate action when a fault has been detected. Unfortunately, fault recovery is not well studied for threaded fastening. The common solutions are the obvious ones: simply abort and retry or signal a human operator for intervention. On considering the cases where billions of products (each containing dozens of screws) are manufactured in automated assembly lines, even a very small screwdriving failure rate in threaded fastening is likely to generate many unqualified products. Hence, these methods are inefficient when applied to high-volume production. The stage classification in [65] points out one possible solution.

VI. Automated Threaded Fastening Systems

Fully automated systems are becoming more popular than manual or semiautomatic fastening equipment for large-scale manufacturing due to their consistent quality and reduced labor costs [66]. A dedicated screwdriving cell, in which multispindled fastening tools can be used to drive multiple screws, is more suitable for high-volume production of a single model due to its advantages in speed and cost. However, just like any other fixed automation system, a changeover can be costly and time-consuming. Despite its possible drawbacks in speed and initial setup cost, robotic screwdriving is becoming popular for lower production rates or frequent design changes [66].

Today, there are many suppliers for automated threaded fastening systems, which includes robots, fastening tools (Section VI-A), and various accessories such as feeders (see Fig. 4), pickup devices (see Section III), and machine vision modules [67]. Among robots, gantry-type and Cartesian robots [68] have high positioning accuracy and large footprint; SCARA robots [22] are often used for electronics assembly; 6-DOF articulated arms [29], [69], [70] can drive screws from different directions to handle complex part geometries; parallel Delta robots [67] enable fast pick-and-place motion. Passive compliance units, such as springs [67], [71], are often used to connect these robots with fastening tools to ease the initial thread mating while maintaining proper insertion force.

Robot sizing and selection is influenced by assembly speed, positioning accuracy, axis of insertion, reaction moments generated by the fastening tool, part geometries, and system integration complexities and other application-specific factors [66], [72]. Generally, small, lightweight robots are used for small screws, Cartesian and SCARA systems for midsize fasteners, and larger, multiaxis robots for midsize and larger fastener sizes. Among these robots, 6-DOF articulated robots offer agility, long reach, and future-use adaptability, and they can handle complex part geometries that may require more than one screw insertion orientations [66].

A. Fastening Tools

Fastening tools, the end-effectors that directly interact with fasteners, determine the screwdriving performance. Both modified manual screwdrivers [71] and specially designed automated fastening tools [27], [68] have been used. In addition, fastening tools vary by the energy transfer method; types include impact tools, (hydraulic) pulse tools, pneumatic tools, and electric tools. In order to choose the proper tool, designers need to consider multiple factors, such as torque range, reaction force, speed, accuracy, environment requirements, and joint hardness [15], [20].

Both impact and pulse tools have high power to weight ratios and low reaction torques. Impact tools, in which tiny hammers give repeated blows on the output anvil, can produce high output torques (10–5000 Nm [20]). However, they are notoriously noisy and inaccurate ($\pm 20\%$ to $\pm 40\%$ [15] and $\pm 30\%$ to $\pm 50\%$ [20]). Pulse tools can apply large torques (3.2–450 Nm) to the fastener in a rapid series of pulses. The best accuracy of pulse tools is $\pm 10\%$ to $\pm 15\%$ [20]. They are much quieter and less violent than their impact cousins, because the torque is not created by hammer blows but rather by hydraulic pulses. Because of the pulse energy transfer process, both impact and pulse tools are sensitive to joint spring rate and frictional losses, and cannot provide data output to an electronic control system [15]. In addition, unlike pneumatic and electric tools [19], there is no ISO standard to define test joints for qualification of such tools [17].

Nut runners are another widely used production bolting tool. They are fast, air- or electric-powered tools used to tighten fasteners requiring torques ranging from 10 to 150 Nm. Smaller sizes of the same tool, often called screwdrivers, generate low torques that rarely exceed 15 Nm [15]. One can adjust the output torque of nut runners ($\pm 7\%$ to $\pm 10\%$ accuracy [20]) through mechanical clutches [15] to disengage the tool when the desired torque has been reached. Broadly speaking, electric tools are usually preferred, because they are quieter, cleaner, and easier to control than air-powered tools in most applications [15]. In addition, electric fastening tools enable more accurate torque outputs via current control ($\pm 5\%$ to $\pm 7\%$ accuracy, inexpensive sensor) or closed-loop torque control ($\pm 1\%$ to $\pm 5\%$ accuracy, expensive sensor) [20].

Current-based torque estimation techniques have been investigated for both dc-powered [6], [73] and ac-powered [74] screwdrivers. In addition, low-cost torque sensing techniques are available for screwdriving applications [71].

Close monitoring of the driving torque and rotation angle can provide valuable information [2], especially for fault detection, as discussed in Section V. In addition, an automatic solution should handle as a wide range of screws as possible [2]. In this case, for example, the replaceable screwdriver bit design [22] can be used to adapt to various screw types. For future threaded fastening tools, intelligent screwdriving system with: fast and reliable operation, accurate yet affordable actuators and sensors, reliable online fault detection and recovery, and ability of easy integration into future manufacturing systems is desired.

VII. Open Problems and Future Directions

Automated threaded fastening has been used in many applications, especially those that require quality, throughput, and consistent monitoring. However, a variety of barriers to further adoption of automated systems remain as follows.

1) Common screw feeding and orientation devices have requirements on the screw aspect ratio (see Section III-A). There are currently no fast and reliable ways to feed screws with smaller length-to-diameter aspect ratios.
2) Automatically starting screws quickly and robustly is difficult [2]. The back-spin first strategy discussed in Section IV seems to be reliable; however, it is slow and requires extra sensing [13]. Moreover, while basic techniques for fault detection have been developed, more sophisticated strategies are necessary for the process to be sufficiently accurate for high-volume use. Strategies for fast and reliable initial thread mating and early fault detection need to be developed.
3) The interface between the screw head and the driver is complex and needs further study. The relationship between axial forces applied by the driver and the efficiency of the torque transfer to the screw is unclear. Minimizing the axial force applied on the screw head is critical in preventing wear on the screw head.
4) Current fault detection strategies cannot detect critical failures such as crossed threads or jammed screws before the parts themselves are damaged. Understanding how to predict such failures and using fault recovery to prevent such failures before the parts are damaged will ensure that threaded fastening failures are less catastrophic.

Of course, the above-mentioned list is not exhaustive, and other application-specific problems may exist. Nevertheless, it provides a basis for determining future research directions. In recent years, for example, miniature assembly automation has become increasingly important [75], especially in the consumer electronics industry [21], [22], [70]. These applications require small screws (≤#4 or ≤M3), miniature screws (M1.6–M3), and microscrews (≤M1.4) [26]. Using such small screws introduces a variety of additional challenges and design considerations [26].

1) *Screw Feeding and Pickup:* Feeding small screws require tighter tolerances on feeding units in general, and often require alternate driving methods such as piezos (as the behavior of magnetic tooling is more inconsistent for small screws) or pickup methods such as vacuum.
2) *Screwdriving:* The fastening tools should offer sufficient torque range and high shut-off accuracy. When driving small screws, it is more difficult to maintain the engagement between the bit and the screw's drive feature. Thus, small screws may impose additional constraints on the design of driving bits, and further research is necessary to understand the specifics and importance of such constraints.
3) *Robotic Systems:* Small screws require high positioning accuracy for the automation system, and thus, alternate locating strategies, such as visual servoing, may be required for correct position and angular alignments [21], [31]. However, the details of these restrictions, and of the intricacies of integrating such a system, are not well understood.

As manufacturers seek to automate more and more of the threaded fastening operation, the challenges presented here will become increasingly pressing. By presenting this analysis of the current state of screwdriving and identifying a selection of open challenges for the research community, we intend to encourage researchers to explore and uncover the science behind screwdriving.

Appendix
Historical Milestones

A brief overview of the significant milestones during the history of threaded fastening is as follows.

15th Century: Screws first appear in medieval weapons. The oldest example dates back to 1475 [76].

19th Century: The demand for screws becomes large enough to warrant factory production. Whitworth devises the world's first national screw thread standard (British standard) in 1841. Sellers presented a uniform system of screw threads in 1864, which later became the U.S. standard [76].

1907: Robertson invents the square socket-head screw. Although it is a major improvement over the slotted screw, it was not widely accepted until later in the form of the hex head screw [76].

1934: Phillips files the patents for the self-centering Phillips-head (cross-head) screw [76], [77] in competition with Robertson's socket head screw.

1936: Phillips screws are used in the manufacturing of the 1936 Cadillac. A number of factors drive manufacturers to choose Phillips screws over the square-socket Robertson screws; the most important reason is their ability to automatically prevent overtorquing. This is the first step toward automatic screwdriving [76].

1968: Gurol and Shoberg, co-founders of GSE Inc., introduce the first commercially available socket wrench torque transducers and battery-powered peak meters [17].

1972: Hayama [49] analyzes thread-forming screws and establishes a model using the minimal energy method.

1973: The Stanford Artificial Intelligence Laboratory presents one of the first examples of robotic assembly. One Stanford arm holds a hinge, while another uses an electric screwdriver to pick up and then insert screws to fix the hinge onto another part [78].

1978: Nevins and Whitney [3] investigate computer-controlled assembly at the Draper Laboratory. In particular, they study the peg-in-hole and threaded assembly, and develop the RCC and the six-axis force/torque sensor [4], [13].

1985: Warnecke *et al.* investigate the screwdriving process with sensor-controlled industrial robots [79]. Milberg *et al.* [30] also investigated robot-aided screwdriving automation.

1988: Peterson *et al.* [80] develop an automated screwdriver for use with industrial robots using an electromagnet bowl feeder and blow feeding.

1990: Tao *et al.* [81] investigate the bolt–nut assembly through compliant coordination control of two PUMA robots.

1990: Nicolson [2] studies dynamic modeling, simulation, and stiffness control of threaded insertions. In 1993, Nicolson and Fearing [8] conduct robotic experiments and find that positioning errors can be easily compensated for, while angular errors (Fig. 7) are more difficult to correct.

1991: Tsujimura and Yabuta [82] develop a model reference adaptive control system for the force control of screwdriving using a 6-DOF manipulator.

1992: Feldmann and Steber study screw fastening in flexible automated assemblies with process control [83].

1995: Dhayagude *et al.* [63] develop a fuzzy logic controller to supervise the integrated process of automated screw fastening while avoiding process-caused failures.

1997: Diftler [39] and Diftler and Walker [40] and [84] apply the “back-spin first” strategy to threaded fastening with a robot hand.

1998: Lara *et al.* [69] develop a robotic screw insertion system for self-tapping screws. Later, they investigate theoretical modeling [48] and fault detection for self-tapping screws [51].

2004: Gaugel *et al.* [85] develop a miniature flexible assembly system, with a transducerized screwdriver as a key module, for the “MiniProd” project.

2006: Wiedmann and Sturges [54], [55] develop kinematic models for thread mating problem in automated assembly.

2007: Heikkilä *et al.* [86] present the first results of the M4-project, a microfactory (TUT-μ Factory) for the assembly of small parts and products. In 2010, they develop a miniaturized flexible screwing cell using vision sensors, an instrumented screwdriver and a Cartesian robot [87].

2013: Matsuno *et al.* [29] develop fault detection algorithms for the screwdriving operation. The experiments implement hybrid position/force control on a 6-DOF articulated arm.

2016: KUKA demonstrates a robotic screwdriving system for tiny (M1) screws for smartphone assembly [70].

2016: Aronson *et al.* [65] divide the robotic screwdriving process into different stages based on which a fault prediction and recovery system for screwdriving can be built.

References

[1] S. Izumi, T. Yokoyama, A. Iwasaki, and S. Sakai, “Three-dimensional finite element analysis of tightening and loosening mechanism of threaded fastener,” *Eng. Failure Anal.*, vol. 12, no. 4, pp. 604–615, 2005.

[2] E. J. Nicolson, “Grasp stiffness solutions for threaded insertion,” M.S. thesis, Dept. Elect. Eng. Comput. Sci., Univ. California, Berkeley, Berkeley, CA, USA, 1990.

[3] J. L. Nevins and D. E. Whitney, “Computer-controlled assembly,” *Sci. Amer.*, vol. 238, no. 2, pp. 62–74, 1978.

[4] J. L. Nevins and D. E. Whitney, “Assembly research,” *Automatica*, vol. 16, no. 6, pp. 195–214, 1980.

[5] L. A. Martin-Vega, H. K. Brown, W. H. Shaw, and T. J. Sanders, “Industrial perspective on research needs and opportunities in manufacturing assembly,” *J. Manuf. Syst.*, vol. 14, no. 1, pp. 45–58, 1995.

[6] B. J. Dunne, “Precision torque control for threaded part assembly,” M.S. thesis, Dept. Mech. Eng., Massachusetts Inst. Technol., Cambridge, MA, USA, 1986.

[7] E. J. Nicolson and R. S. Fearing, “Dynamic modeling of a part mating problem: threaded fastener insertion,” in *Proc. IEEE RSJ Int. Workshop Intell. Robots Syst.*, 1992, pp. 30–37.

[8] E. J. Nicolson and R. S. Fearing, “Compliant control of threaded fastener insertion,” in *Proc. ICRA*, 1993, pp. 484–490.

[9] L. G. Allen, “Fastener failure: Who duunit? What’s to be done about it?” *Automation*, Nov. 1988.

[10] P. G. Myer, “IXTOC I: Case study of a major oil spill,” M.A. thesis, Dept. Marine Affairs, Univ. Rhode Island, Kingston, RI, USA, 1984.

[11] *Top 10 Worst Oil Spills*. Accessed: Sep. 30, 2015. [Online]. Available: http://www.livescience.com/6363-top-10-worst-oil-spills.html

[12] M. Finkenbiner, *Atlas Copco Tools and Assembly Systems Advanced Fastening Technology*. Nacka, Sweden: Atlas Copco, 2010.

[13] D. E. Whitney, *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development*. London, U.K.: Oxford Univ. Press, 2004, vol. 1.

[14] J. H. Bickford, *Handbook of Bolts and Bolted Joints*. Boca Raton, FL, USA: CRC Press, 1998.

[15] J. H. Bickford, *Introduction to the Design and Behavior of Bolted Joints*. Boca Raton, FL, USA: CRC Press, 2007.

[16] *Screw Thread Design Fundamentals*, Fastenal, Winona, MN, USA, 2009.

[17] R. S. Shoberg, “Engineering fundamentals of threaded fastener design and analysis. I,” *Fastening*, vol. 6, no. 2, pp. 26–29, 2000.

[18] D. Croccolo, M. De Agostinis, and N. Vincenzi, “Failure analysis of bolted joints: Effect of friction coefficients in torque–preloading relationship,” *Eng. Failure Anal.*, vol. 18, no. 1, pp. 364–373, 2011.

[19] *Rotary Tools for Threaded Fasteners—Performance Test Method*, document ISO 5393:2017, 2013.

[20] *Basic Techniques of Threaded Fastening (Training Materials)*, Desoutter Industrial Tools, London, U.K., 2013.

[21] E. Järvenpää, M. Lanz, and R. Tuokko, “Capability-based adaptation of production systems—Practical case study in TUT-microfactory environment,” in *Key Eng. Mater.*, vol. 572, pp. 245–248, Sep. 2014.

[22] Z. Li. *Robotics Research for 3C Assembly Automation*. Accessed: Jan. 2015. [Online]. Available: https://app.box.com/s/zcg8qqxt6fw6v4xz22h6

[23] VS Inc. *Electric Drive Pro-Fuse Screw Tape Feeder*. Accessed: Sep. 30, 2015. [Online]. Available: http://www.hp-vanguard.com/

[24] G. Boothroyd *et al.*, *Assembly Automation and Product Design*, vol. 536. Cambridge, U.K.: Cambridge Univ. Press, 2005.

[25] WSS Inc. *Zep120 Mini Piezo Step Feeder*. Accessed: Apr. 2015. [Online]. Available: http://www.weberusa.com/product/feeders/micro-feeder-2

[26] A. Weber, “Automation for small screws,” *Assembly*, vol. 55, no. 2, pp. 40–43, 2012.

[27] *Eelectric Screwdriver General Catalog*, HIOS Inc., Matsudo, Japan, 2013.

[28] T. J. Han and M. Singh, “Methods, devices and systems for screw feeding by vacuum and gravity,” U.S. Patent 7,178,432, Feb. 20, 2007.

[29] T. Matsuno, J. Huang, and T. Fukuda, “Fault detection algorithm for external thread fastening by robotic manipulator using linear support vector machine classifier,” in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2013, pp. 3443–3450.

[30] J. Milberg, C. Maier, and H. Wamecke, “Contribution to the automation of screwdriving with the aid of industrial robots,” *CIRP Ann.-Manuf. Technol.*, vol. 34, no. 1, pp. 49–52, 1985.

[31] S. Pitipong, P. Pornjit, and P. Watcharin, “An automated four-DOF robot screw fastening using visual servo,” in *Proc. IEEE/SICE Int. Symp. Syst. Integr. (SII)*, Dec. 2010, pp. 379–383.

[32] K. Ogiso and M. Watanabe, “Increase of reliability in screw tightening,” in *Proc. 4th Int. Conf. Assem. Autom.*, 1982.

[33] G. Fantoni *et al.*, “Grasping devices and methods in automated production processes,” *CIRP Ann.*, vol. 63, no. 2, pp. 679–701, 2014.

[34] G. J. Monkman, S. Hesse, R. Steinmann, and H. Schunk, *Robot Grippers*. Hoboken, NJ, USA: Wiley, 2007.

[35] K. Dharmaraj, "Automated freeform assembly of threaded fasteners," Ph.D. dissertation, School Mech. Manuf. Eng., Loughborough Univ., Loughborough, U.K., 2015.

[36] I. L. Blaer, "Reliable automatic starting of threaded parts," *Russian Eng. J.*, vol. 42, no. 12, pp. 32–34, 1962.

[37] *MicroTorque-ToolsTalk MT User Guide*, Atlas Copco, Nacka, Sweden, 2010.

[38] K. H. Brown, C. Morrow, S. Durbin, and A. Baca, "Guideline for bolted joint design and analysis: Version 1.0," Sandia Nat. Lab., Albuquerque, NM, USA, Sandia Rep. SAND2008-0371, Jan. 2008. [Online]. Available: http://prod.sandia.gov/techlib/access-control.cgi/2008/080371.pdf

[39] M. A. Diftler, "Alignment of threaded parts using a robot hand: Theory and experiments," Ph.D. dissertation, Dept. Mech. Eng. Mater. Sci., Rice Univ., Houston, TX, USA, 1998.

[40] M. A. Diftler and I. D. Walker, "Experiments in aligning threaded parts using a robot hand," *IEEE Trans. Robot. Autom.*, vol. 15, no. 5, pp. 858–868, Oct. 1999.

[41] I. G. Romanov, "Preventing thread shear in automatic assembly," *Russian Eng. J.*, vol. 44, no. 9, pp. 50–52, 1964.

[42] D. L. Dean, "Design of a robotic end-effector for automated bolting," M.S. thesis, Dept. Mech. Eng., Massachusetts Inst. Technol., Cambridge, MA, USA, 1985.

[43] D. E. Whitney, "Quasi-static assembly of compliantly supported rigid parts," *J. Dyn. Syst., Meas., Control*, vol. 104, no. 1, pp. 65–77, 1982.

[44] J. T. Boys and P. W. Wallace, "Design and performance of an automatic control system for fastener tightening," *Proc. Inst. Mech. Eng.*, vol. 191, no. 1, pp. 371–380, 1977.

[45] *Fundamentals of Threaded Fastening (Training Materials)*, Ingersoll Rand Inc., 2013.

[46] S. K. Smith, "Use of a microprocessor in the control and monitoring of air tools while tightening threaded fasteners," in *Proc. Soc. Manuf. Eng.*, Dearborn, MI, USA, 1980, pp. 397–421.

[47] P. Stéphan, F. Mathurin, and J. Guillot, "Experimental study of forming and tightening processes with thread forming screws," *J. Mater. Process. Technol.*, vol. 212, no. 4, pp. 766–775, 2012.

[48] L. Seneviratne, F. A. Ngemoh, S. W. E. Earles, and K. A. Althoefer, "Theoretical modelling of the self-tapping screw fastening process," *Proc. Inst. Mech. Eng. C, J. Mech. Eng. Sci.*, vol. 215, no. 2, pp. 135–154, 2001.

[49] M. Hayama, "Estimation of torque in cold forming of internal thread," *Bull. Faculty Eng. Yokohama Nat. Univ.*, vol. 21, pp. 77–90, Mar. 1972.

[50] M. Klingajay, L. D. Seneviratne, and K. Althoefer, "Identification of threaded fastening parameters using the newton raphson method," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, vol. 2, Oct. 2003, pp. 2055–2060.

[51] K. Althoefer, B. Lara, Y. H. Zweiri, and L. D. Seneviratne, "Automated failure classification for assembly with self-tapping threaded fastenings using artificial neural networks," *Proc. Inst. Mech. Eng. C, J. Mech. Eng. Sci.*, vol. 222, no. 6, pp. 1081–1095, 2008.

[52] K. Althoefer, B. Lara, and L. D. Seneviratne, "Monitoring of self-tapping screw fastenings using artificial neural networks," *J. Manuf. Sci. Eng.*, vol. 127, no. 1, pp. 236–243, 2005.

[53] T. Lozano-Pérez, M. T. Mason, and R. H. Taylor, "Automatic synthesis of fine-motion strategies for robots," *Int. J. Robot. Res.*, vol. 3, no. 1, pp. 3–24, 1984.

[54] S. Wiedmann and B. Sturges, "A full kinematic model of thread-starting for assembly automation analysis," *J. Mech. Des.*, vol. 128, no. 1, pp. 128–136, 2006.

[55] S. Wiedmann and B. Sturges, "Spatial kinematic analysis of threaded fastener assembly," *J. Mech. Des.*, vol. 128, no. 1, pp. 116–127, 2006.

[56] R. Chumakov, "An artificial neural network for fault detection in the assembly of thread-forming screws," *J. Intell. Manuf.*, vol. 19, no. 3, pp. 327–333, 2008.

[57] M. Ruusunen and M. Paavola, "Quality monitoring and fault detection in an automated manufacturing system—A soft computing approach," Dept. Process. Environ. Eng., Control Eng. Lab., Univ. Oulu, Oulu, Finland, Tech. Rep. 19, 2002.

[58] R. Isermann, *Fault-Diagnosis Systems: An Introduction from Fault Detection to Fault Tolerance*. Berlin, Germany: Springer, 2006.

[59] R. Isermann, *Fault-Diagnosis Applications: Model-Based Condition Monitoring: Actuators, Drives, Machinery, Plants, Sensors, and Fault-tolerant Systems*. Berlin, Germany: Springer, 2011.

[60] A. Grauel, L. A. Ludwig, and G. Klene, "Comparison of different intelligent methods for process and quality monitoring," *Int. J. Approx. Reasoning*, vol. 16, no. 1, pp. 89–117, 1997.

[61] B. Lara, K. Althoefer, and D. Seneviratne, "Use of artificial neural networks for the monitoring of screw insertions," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, vol. 1, Oct. 1999, pp. 579–584.

[62] M. Klingajay and N. I. Giannoccaro, "The automated threaded fastening based on on-line identification," *Int. J. Adv. Robot. Syst.*, vol. 1, no. 4, pp. 263–272, 2004.

[63] N. Dhayagude, Z. Gao, and F. Mrad, "Fuzzy logic control of automated screw fastening," *Robot. Comput.-Integr. Manuf.*, vol. 12, no. 3, pp. 235–242, 1996.

[64] C. Deters, H.-K. Lam, E. L. Secco, H. A. Wurdemann, L. D. Seneviratne, and K. Althoefer, "Accurate bolt tightening using model-free fuzzy control for wind turbine hub bearing assembly," *IEEE Trans. Control Syst. Technol.*, vol. 23, no. 1, pp. 1–12, Jan. 2015.

[65] R. M. Aronson *et al.*, "Data-driven classification of screwdriving operations," in *Proc. Int. Symp. Experim. Robot.*, 2016, pp. 244–253.

[66] A. Weber, "Robotic screwdriving-flexible systems help drive down production costs," *Assem.-Radnor*, vol. 48, no. 11, pp. 38–47, 2005.

[67] FANUC. Accessed: Feb. 2015. [Online]. Available:http://robot.fanucamerica.com

[68] Atlas Copco. Accessed: Jan. 2015. [Online]. Available: http://www.atlascopco.us

[69] B. Lara, K. Althoefer, and L. D. Seneviratne, "Automated robot-based screw insertion system," in *Proc. 24th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, vol. 4, Aug. 1998, pp. 2440–2445.

[70] *Kuka Ready2_Fasten_Micro*, KUKA, Augsburg, Germany, 2016.

[71] J.-Y. Hwang, D.-H. Jung, Y.-J. Roh, K.-J. Nam, and D.-Y. Hwang, "Low-cost automatic screw machine using a commercial electric screwdriver," in *Proc. IEEE 12th Int. Conf. Control, Autom. Syst. (ICCAS)*, Oct. 2012, pp. 1055–1060.

[72] K. Takada, "Fujitsus approaches to developing smartphones," *FUJITSU Sci. Tech. J.*, vol. 49, no. 2, pp. 146–152, 2013.

[73] K. Althoefer, L. D. Seneviratne, and R. Shields, "Mechatronic strategies for torque control of electric powered screwdrivers," *Proc. Inst. Mech. Eng. C, J. Mech. Eng. Sci.*, vol. 214, no. 12, pp. 1485–1501, 2000.

[74] M. Matsumura, S. Itou, H. Hibi, and M. Hattori, "Tightening torque estimation of a screw tightening robot," in *Proc. IEEE Int. Conf. Robot. Autom.*, vol. 2, May 1995, pp. 2108–2112.

[75] H. N. Hansen, M. Arentoft, G. Tosello, and A. Gegeckaite, "Micro-mechanical-assembly," in *Micromanufacturing Engineering and Technology*, Y. Qin, Ed. 2010, pp. 174–184.

[76] W. Rybczynski, *One Good Turn: A Natural History of the Screwdriver and the Screw*. New York, NY, USA: Scribner, Jul. 2013.

[77] H. F. Phillips, "Screw," U.S. Patent 2 046 343, Jul. 7, 1936.

[78] K. Pingle, R. Paul, and R. Bolles, "Programmable assembly, three short examples," Film, Stanford AI Lab., 1974. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/9297/

[79] H. Warnecke, E. Abele, J. Walther, and G. Fischer, "Investigations of the screw driving process with sensor-controlled industrial robots," *CIRP Ann.-Manuf. Technol.*, vol. 34, no. 1, pp. 41–44, 1985.

[80] G. P. Peterson, B. D. Niznik, and L. M. Chan, "Development of an automated screwdriver for use with industrial robots," *IEEE J. Robot. Autom.*, vol. 4, no. 4, pp. 411–414, Aug. 1988.

[81] J. M. Tao, J. Y. S. Luh, and Y. F. Zheng, "Compliant coordination control of two moving industrial robots," *IEEE Trans. Robot. Autom.*, vol. 6, no. 3, pp. 322–330, Jun. 1990.

[82] T. Tsujimura and T. Yabuta, "Adaptive force control of screwdriving with a positioning-controlled manipulator," *Robot. Auto. Syst.*, vol. 7, no. 1, pp. 57–65, 1991.

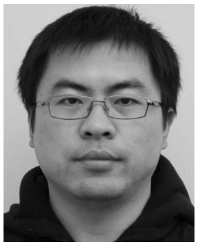
[83] K. Feldmann and M. Steber, "Screw fastening in flexible automated assembly with computer-integrated process control," *CIRP Ann.*, vol. 41, no. 1, pp. 41–44, 1992.

[84] M. A. Diftler and I. D. Walker, "Determining alignment between threaded parts using force and position data from a robot hand," in *Proc. IEEE Int. Conf. Robot. Automat.*, vol. 2, Apr. 1997, pp. 1503–1510.

[85] T. Gaugel, M. Bengel, and D. Malthan, "Building a mini-assembly system from a technology construction kit," *Assem. Autom.*, vol. 24, no. 1, pp. 43–48, 2004.

[86] R. H. Heikkilä, I. T. Karjalainen, J. J. Uusitalo, A. S. Vuola, and R. O. Tuokko, "Possibilities of a microfactory in the assembly of small parts and products-first results of the M4-project," in *Proc. IEEE Int. Symp. Assem. Manuf. (ISAM)*, Jul. 2007, pp. 166–171.

[87] A. Vuola *et al.*, "Miniaturization of flexible screwing cell," in *International Precision Assembly Seminar*. Berlin, Germany: Springer, 2010, pp. 309–316.



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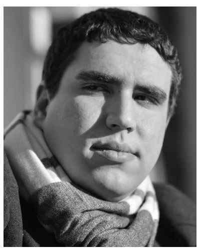

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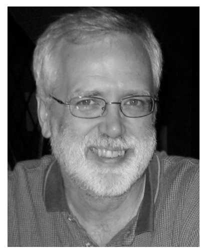

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