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CASE STUDY IN BIOMIMETIC DESIGN: HANDLING AND ASSEMBLY OF MICROPARTS

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ABSTRACT

This paper describes the application of the biomimetic design process to the development of automated gripping devices for microparts.

Handling and assembly of micromechanical parts is complicated by size effects that occur when part dimensions are scaled down. A common complication involves sticking between the gripping device and the micropart, which hinders the automation of picking and releasing operations. This paper presents the identification and use of biological analogies to solve the problem of sticking during microassembly. Selected release techniques based on DNA transcription and the abscission process in plants inspired concepts of new automated handling devices for microobjects.

The design, development and testing of a gripping device, based on biological principles, for the automated handling and assembly of a microscrew is presented.

1 INTRODUCTION

This paper describes the application of the biomimetic design process to the development of automated gripping devices for microparts. Biomimetic design involves the identification and use of biological analogies to solve problems in engineering. First, a summary of related and previous work on biomimetic design will be provided. Next, difficulties which arise in the handling of parts at the micro level that do not arise at the macro level, will be described. A search for biological analogies that may be used to solve these difficulties resulted in several relevant biological phenomena, two of which will be summarized here. The strategies from these phenomena will be highlighted, and the physical implementation and experimental validation of one strategy will conclude this paper.

2 RELATED AND PAST WORK

Biomimetic design uses biological phenomena as analogies to help solve engineering problems. One well-known example of biomimetic design is the development of Velcro after observing that cockleburs attach to clothing and fur. First presented in this section will be related work in analogical reasoning and design by analogy. Next described is how biomimetic design fits into the technique of synectics and how TRIZ is relevant to biomimetic design. Finally, past work in biomimetic design is summarized.

2.1 Analogical Reasoning

Analogical reasoning involves the transfer of information from a source to a target domain. Within-domain analogies are used between the same or at least conceptually close, source and target domains, e.g., from one type of electromechanical product to another. Between-domain analogies are used between different source and target domains, e.g., from biological phenomena to electro-mechanical products.

Benami and Jin (2002) developed a Cognitive Model of Creative Conceptual Design that captures the relationship between the properties that stimulate cognitive processes and the design operations that facilitate cognitive processes. One conclusion of the study was that ambiguous entities stimulated more ideas than non-ambiguous entities, which tend to be fixating. Also noted is that analogies from conceptually different domains result in more creative, original ideas.

2.2 Related Work in Design by Analogy

A number of design frameworks exist for facilitating the abstraction of within-domain analogies. Of these, there are knowledge-based systems that rely on surface similarity, such as Syn, where topological patterns of air circulation systems are matched with the requirements of the given architectural design problem (Goel 1997). More complex is the Ideal system developed by Bhatta and Goel (1994) that evaluates functional and causal patterns with no topological information such that functional similarities are explored.

McAdams and Wood (2000) developed a quantitative metric for design-by-analogy, which is based on the functional similarity of products within the domain of engineering. One goal of the metric is to reveal analogies between the functional requirements of the product to be designed and products that are similar, at a level that is useful for concept generation. Relationships between product functions and customer needs result in a procedure where critical functions of existing products can be adapted to solve the design problem of interest.

2.3 Synectics and Biological Analogies

Synectics is a technique for creative thinking that uses four types of analogies: direct, personal, symbolic, and fantasy. In the development of synectics, Gordon (1961) observed that biology provided the richest source of direct analogies. Many design textbooks suggest biological systems as a promising source of analogies (Dieter 2000, Ulrich & Eppinger 2000, Otto & Wood 2001, Hyman 2003, Dym & Little 2004). However, what remains unavailable to engineering students and practicing engineers are tools to formally support the identification and use of biological analogies for design. Many engineers do not have sufficient knowledge of biological phenomena to recall the most relevant biological analogies for a given design problem. When pressed, the biological analogies that come to mind are typically the most obvious and thus less likely to lead to creative solutions.

2.4 TRIZ and Biomimetic Design

The Theory of Inventive Problem Solving (TRIZ) is a method used to trigger creativity in problem solving (Altshuller 1984). The foundation of TRIZ is the compilation and organization of technical knowledge through the analysis of patents. Recurring engineering conflicts and their solutions were identified and categorized into the TRIZ database. To use TRIZ, challenges of the design problem are matched with a list of engineering conflicts. Possible design principles are then suggested to overcome contradictions.

Relevant to supporting biomimetic design, Vincent and Mann (2002) propose the extension of the TRIZ database to include biological information and principles.

2.5 Past Work in Biomimetic Design

Compiling and updating a suitably expansive database is resource intensive and may be subject to the compilers' own knowledge and bias. Our approach is to take advantage of the enormous amount of biological information already available in natural-language format, such as books, journals, etc. Instances of functional keywords are sought in the biological corpus, or body of text. Matches, or text excerpts containing keywords, are examined for relevant biological phenomena that can be applied towards the engineering problem. Our initial biological corpus is an introductory university-level textbook: Life, the Science of Biology (Purves et al., 2001). Verbs are used to formulate keywords because they convey functionality (Stone & Wood, 1999; Ullman, 2003). Once relevant phenomena have been identified, further details can easily be obtained using other sources.

Past case studies using this method include those in design for remanufacture (Vakili & Shu, 2001; Hacco & Shu, 2002) and centering in microassembly (Shu et al., 2003). Fundamental work performed to improve this method includes observations of how descriptions of biological phenomena are used to solve problems (Mak & Shu 2004a, 2004b) and exploration of linguistic approaches for generating alternative keywords (Chiu & Shu, 2004, 2005). The work described in this paper uses the results of past fundamental work and implements the biological strategy into a physical solution that can be tested.

3 PROBLEM DEFINITION

While biology serves as a rich, largely untapped source of information for engineering, biomimetic design may be particularly appropriate for finding solutions for micro or even nano scale engineering problems, since many biological processes occur in the same scale. Biological phenomena have been used to design for example, microfluidic devices with specific functionality (Shevkoplyas et al., 2005).

Biomimetic design will be used to develop novel gripper principles that overcome surface force challenges specific to microassembly. Biological principles that address analogous problems will be described. These principles will be used to develop feasible solutions for the automated handling and insertion of microscrews specifically. The unique feature of this case study is that physical implementation based on a chosen biological strategy was performed and tested.

3.1 Challenges in Microassembly

Assembly is a fundamental process in product fabrication. Products consist of separate parts for many reasons, e.g., material differentiation, product complexity, and manufacturing process incompatibility, etc. Since the assembly of microproducts is particularly challenging, a strategy is to reduce as much as possible the manipulation of microcomponents through a greater amount of component integration as compared with conventional-sized products (Alting et al., 2003). The additional challenges specific to the assembly of microcomponents, or microassembly, are due to the reduced dimensions involved (Van Brussel et al., 2000):

- In the micro regime, submicron precision is often required (Reinhart & Höhn, 2000).
- At the micro level, surface-related forces, such as electrostatic, Van der Waals and surface tension forces dominate gravitational forces.

• Manual handling of microparts is impeded by loss of direct hand-eye coordination, as microscopes are required for vision and microgrippers are required for manipulation.

To achieve good visual resolution, high magnification is used on a microscope, which then results in a restricted field of view (often smaller than the object), a very short depth of focus (limited visual clarity) and short working distance. Reduction in magnification to increase the field of view is possible, but only at the cost of resolution. Furthermore, microgrippers have fewer degrees of freedom than the human hand and generally provide no force feedback.

• Manual handling of microparts is time consuming, leading to high production costs.

Automated assembly technologies for microproducts are required if mass production is to be realized. However, it may be necessary to move beyond downscaling existing processes and technologies to accommodate smaller components. In some cases, the development of totally new assembly technologies to replace conventional processes is necessary.

3.2 Characteristics of Specific Microobject

This paper addresses the problems of picking up, correctly positioning and tightening a metal screw of 0.6 mm diameter. Such screws, used for example in hearing-aid components, are currently handled and inserted manually into plastic components. It is relatively difficult to obtain the strength and reliability of these joints using other fastening methods. Therefore the automation of the handling and insertion of such screws is of interest, which requires overcoming the challenges previously mentioned.

The focus of our problem is to develop a grasping and releasing mechanism for microgrippers that overcomes adhesion due to surface forces between components. Such forces are significant for microcomponents because the gravitational forces acting on objects decrease with size while surface forces essentially remain the same or decrease at a lower rate (Van Brussel et al., 2000). These surface forces depend on gripper design and many efforts have been made to minimize their effects through diverse gripper mechanisms and configurations. Different working principles include mechanical, aerostatic, electrostatic, magnetic and optical pressure grippers (Van Brussel et al., 2000, Sanchez-Salmeron et al., 2005). In addition, contact-type gripper surfaces have been developed with maximum roughness (Arai et al., 1996) to minimize surface contact and thus van der Waals forces.

4 BIOLOGICAL ANALOGIES

In this section, we describe two biological phenomena relevant to developing a novel gripper design that overcomes sticking effects that especially complicate the automated grasping and releasing of microobjects. Guided by results of past work on finding suitable keywords to locate biological analogies, "release" is a troponym, or specific manner, of "remove" (Chiu and Shu, 2004). A biologically connotative keyword for "remove" is "defend" (Chiu and Shu, 2005) since entities are sometimes removed in biological systems as a defensive mechanism.

4.1 DNA Transcription

Biological Phenomenon

A match with "defend" identified the concept of regulated expression of interferons, which are proteins that defend against viral infections. The regulated expression, or controlled production, of proteins results from the following.

In biology, transcription is the process of synthesizing ribonucleic acid (RNA) using one strand of deoxyribonucleic acid (DNA) as the template. RNA is then used to synthesize proteins, e.g., that can defend against viral infections. Discrete segments of the DNA, i.e., different genes, encode different proteins and these genes are transcribed and then translated into proteins. Since different proteins are synthesized as needed for specific purposes, the activities of several molecules (also proteins) determine whether the transcription process is carried out, and where along the DNA the transcription occurs.

Figure 1a shows that the activator protein binds to a region of the DNA that is some distance away from where the proteins that form the transcription complex bind to the DNA. It is hypothesized that the DNA is bent such that the activator protein can contact the transcription complex, as shown in Figure 1b, to stimulate the transcription process (Purves et al., 2001). The specific binding of proteins involved is governed by their particular geometries and the molecular interactions between the proteins and the proteins and the DNA.

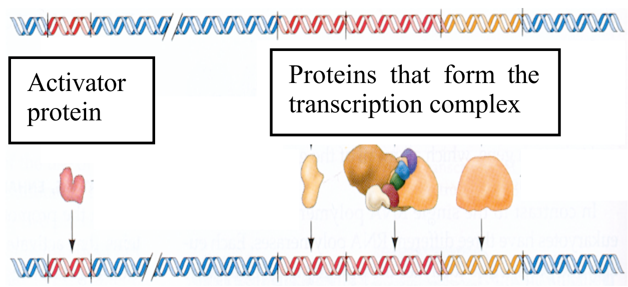

Figure 1a: Proteins and binding regions on DNA

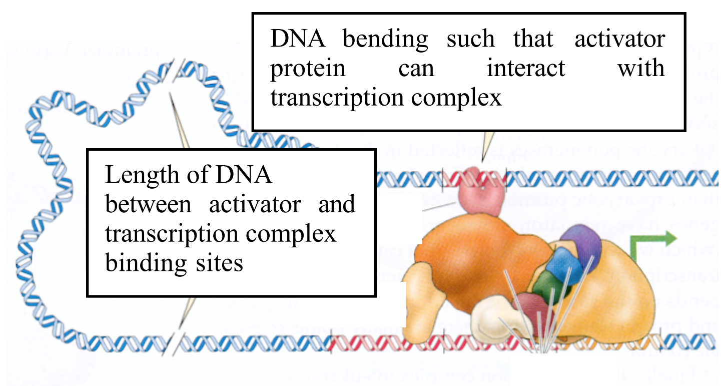

Figure 1b: Interaction of activator protein and transcription complex bound to different regions of DNA. Adapted with permission, Purves et al. (2001).

Application to Microassembly

The strategy extracted from the above biological phenomenon is as follows. Interactions due to specific geometries (or chemical characteristics) of entities as they move relative to each other determine whether proteins are synthesized in biology (to enable defense against, or removal of, invasive entities), and whether a microobject is released for our problem.

Proposed Solution

A possible physical realization of the above strategy is a ribbon-like structure with features that either grip or release microobjects based on the amount of surface area in contact with the microobject. A highly simplified schematic is shown in Figure 2. As the structure is rotated, features move relative to each other and the microobject. The geometry of the gripping features is such that sufficient contact with the object ensures a secure grip when the object is between these features. To release the object, the ribbon is rotated until the object is between the features that minimize contact. When the two sides of the ribbon are then pulled apart, the object will be released with minimal surface interactions.

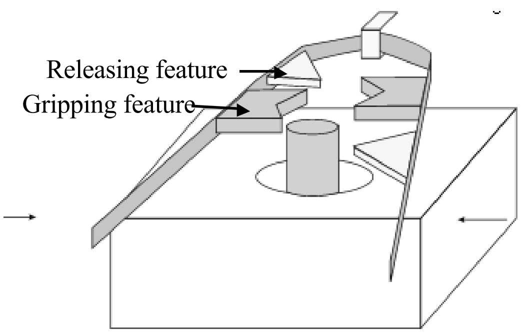

Figure 2: Proposed micro handling tool inspired by DNA transcription.

Analogical mapping between the source and target domains, guided by past work (Mak and Shu, 2004b) is as follows. The strategy used for the controlled production of proteins that remove invasive entities in biology is transferred to the controlled release of microobjects. Chemical and geometric interactions between entities bound to different regions of DNA as portions of DNA move past each other is the mechanism behind the biological phenomenon. Physically, the DNA strand maps into the ribbon structure of the above concept, and the reactants map onto the geometric features attached to the ribbon structure. Geometric interactions between these features and the microobject are used to enable the release of the microobject by minimizing surface effects.

4.2 Abscission

Biological Phenomenon

Many keywords, e.g., “defend”, “remove” and “release” can be used to locate the phenomenon of abcission, the process by which leaves, petals, and fruits separate from a plant. Plants direct growth in different parts such as roots and shoots by strategically releasing a hormone called auxin. When leaves are damaged through infection for example, or are no longer needed, as in the winter season, the leaves stop producing auxin, allowing the further expression of abscisic acid and ethylene, which advance abscission. As a result, specific parts of the stalks of the leaves break down and become completely detached from the plant. The base of some leaves contains a special layer of cells called the abscission zone (see Figure 3). In the absence of auxin, these cells swell and form a cork-like material. This cuts off the flow of nutrients to the leaf and forms a seal between the leaf and the plant and protects the plant once the leaf separates (Purves et al., 2001).

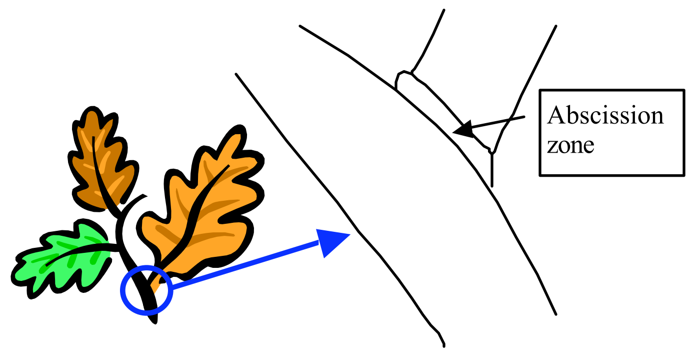

Figure 3: Abscission zone.

Application to Microassembly

The strategy extracted from the abscission phenomenon is that an intermediate zone, which can be broken down, is used to enable separation, of leaf from plant, and of microobject from gripper. The adhesive effects between the gripper surface and the component can be avoided by eliminating the need to separate the two via the traditional concept of release. This could be achieved by designing “large” micro-grippers that remain stuck to the part and are detached from the end-effector of for example, a robot after positioning has been achieved. The sacrificial part of the tool can then be eliminated (and thereby the microcomponent detached) by “breaking it down” from the component using post-processes such as heating or immersing in a suitable solvent.

Proposed Solution

To overcome difficulties associated with the object adhering to the handling device, the object is released together with a part of the tool designated as sacrificial (see Figure 4). The sacrificial part is of significant mass to take advantage of gravity. In this way the object can be easily released. The sacrificial part of the tool can then either remain with the microobject or be subsequently removed. The analogical mapping for this case is quite straightforward: the gripper maps to the plant, the sacrificial part of the tool to the abscission zone, and the microobject that is released to the leaf. Breaking down of the abscission zone or sacrificial part of the tool results in the desired final separation.

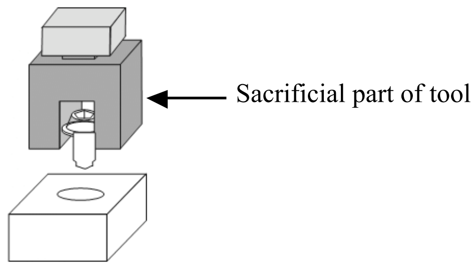

Figure 4: Principle of abscission applied to microassembly.

4.3 Discussion

The solutions proposed above require evaluation with respect to advantages and possible challenges. The first solution (Figure 2) requires the development of a device containing the ribbon with gripping and releasing features. The second solution can be implemented using far simpler techniques. An available technology uses ice between the gripper and the microobject (Kochan, 1997). This could be interpreted as a possible implementation of the abscission principle. The difference from our proposed solution is that the microobject is not to be released due to an increased gravitational force, but due to the melting of the ice. The next section describes our actual physical implementation of the abscission strategy to release a specific microscrew, which differs slightly from the general concept proposed.

5 PHYSICAL IMPLEMENTATION OF ABSCISSION

5.1 Characteristics of Microobject

The microobject of interest is a 0.6 mm microscrew with a pitch of 0.125 mm and a head diameter of 1.15 mm. The screw is metallic and typically gold coated. The screw is to be assembled into a plastic counterpart typically made of polypropylene, shown in Figure 5.

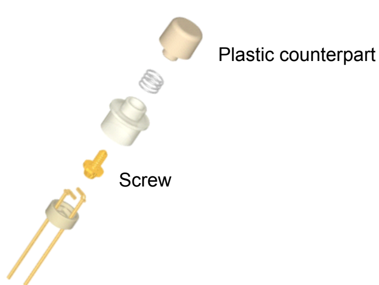

Figure 5: Assembly containing microscrew of interest (www.sonion.com, 2006).

5.2 Experimental Setup

Chosen for this investigation is a small industrial robot with six degrees of freedom and a specified repeatability of ± 0.02 mm, the highest in its class. It is currently used in many industrial processes for different handling operations of primarily macro scale parts. Before using the robot for this particular investigation, a full calibration of repeatability and positioning accuracy within the working volume of the robot was performed (Ericksson et al., 2005). The performance proved to match the specifications. The robot is meant to be a central part of a so-called microfactory. However, the end-effector of the robot and the available grippers are not suitable for microobjects. The robot is placed on a granite table in a temperature-controlled room (20±1°C) at the Technical University of Denmark.

The abscission zone is physically implemented as a polypropylene rod of 4 mm diameter that is easily gripped and positioned by the robot. The tip of the polypropylene rod is locally melted by heating, and then pressed over the head of the screw. The contact with the screw results in solidification of the polypropylene, and a solid bond between the rod and the screw is formed. The robot can now manipulate the screw into the plastic counterpart. Once the screw is tightened into its final position, the resulting increased torque will break the bond between screw and rod.

Other concepts considered for implementation of the abscission principle included the use of ice or other intermediate material that could be chemically dissolved. This however would introduce possible contaminants that are clearly undesirable. The abscission principle is more broadly interpreted as a physically weaker zone between the tree (gripper) and the leaf (screw). Gravitational, torsional or other forces can be used to break this zone to separate the gripper and screw. In addition to relative "weakness", another factor that led to the choice of a polymer as the intermediate-zone material is the ability of polymers to form the very small geometric features that mate with and thus handle the microscrew.

5.3 Experimental Procedure

The robot was programmed to automatically pick up a polypropylene rod and move it to a heating zone. After heating the rod for a specified period of time, the rod was pressed against the head of a screw mounted vertically in a tray. The screw is then moved to the desired position and tightened into the plastic substrate. Figure 6 contains a schematic of the setup (footprint approximately 500 mm x 400 mm). Figures 7-9 are photographs that show various components of the physical setup.

Two different grades of polypropylene were used for the rod. Furthermore, the heating temperature was varied in increments from 160°C to 240°C. The rod was held at the heating zone for 10 seconds, and subsequently pressed over the head of the screw for 10 seconds. The diameter of the hole in the plastic counterpart was 0.4 mm.

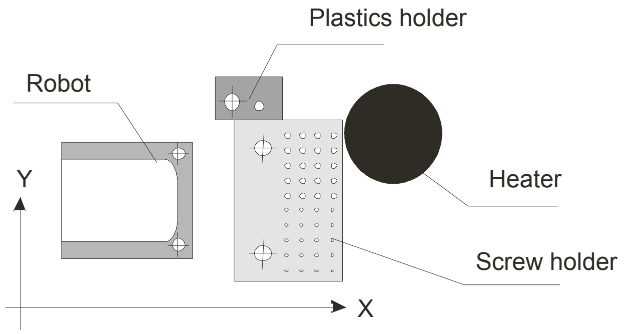

Figure 6: Top-view diagram of experimental setup.

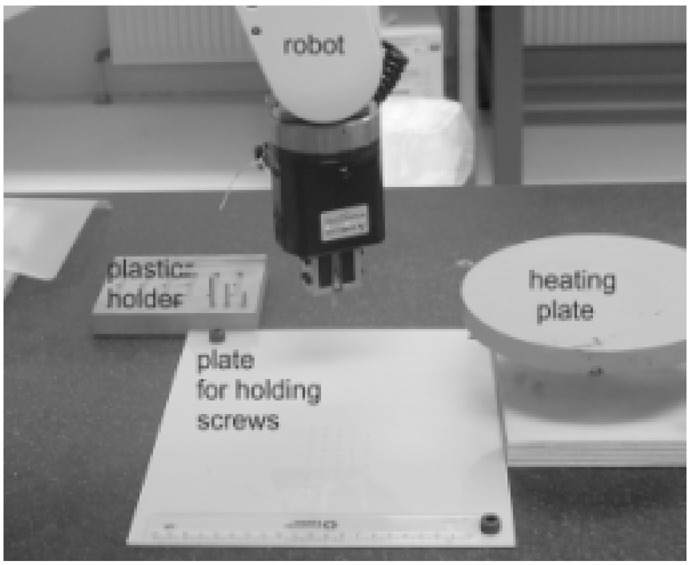

Figure 7: Experimental setup.

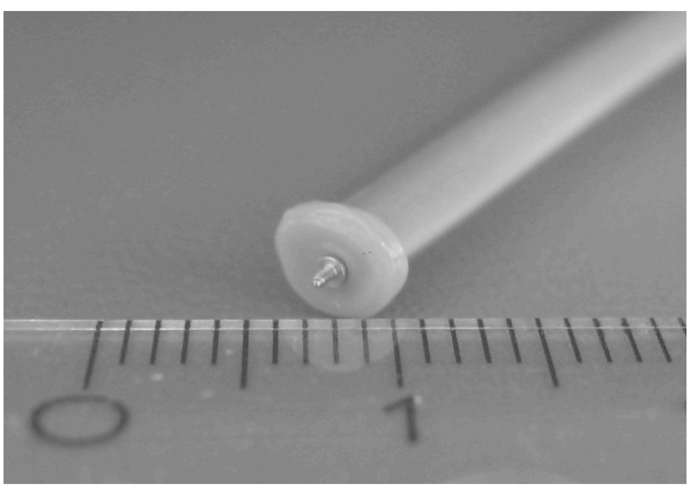

Figure 8: Polypropylene rod with screw.

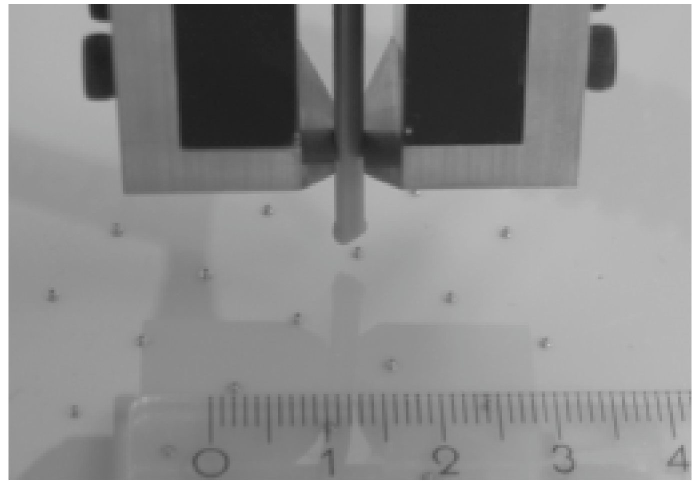

Figure 9: Gripper with polypropylene rod.

5.4 Results

The experiments demonstrated that the abscission strategy was developed into a viable concept for automated handling and release of the microscrew. The bonding strength between the polypropylene rod and the screw proved sufficient to ensure a secure fastening of the screw in a plastic counterpart. The temperature of the heating device is the most critical parameter to ensure the proper bonding strength. It was observed that when using temperatures below 180°C, the screw could not be successfully tightened into the substrate. When the polypropylene rod is heated in the interval between 180°C and 200°C, the actual assembly process follows the desired abscission-inspired behavior as described in Section 5.2. If the polypropylene rod is heated above 200°C, the screw is not released directly after tightening. In this case, it is necessary to apply a separate pull force with the robot to detach the screw from the polypropylene rod. This is explained by the fact that the plastic material is melted to a higher degree at these temperatures and therefore tends to flow into a small hexagonal feature in the head of the screw.

The industrial robot was observed to have sufficient repeatability to perform this operation. A critical factor is the alignment of the polypropylene rod in the robot. If one rod is used repeatedly, the position and orientation of the rod tip must be well known for robot control purposes. If however a rod is only used once and then replaced by a new rod for each screw, the rod must be consistently positioned, e.g., using a fixture, within the robot to not require vision systems and feedback loops. In either case, a vision system and feedback loops would increase accuracy and thereby the expected yield of the process.

6 CONCLUSIONS

This paper described the identification and use of biological analogies to inspire solutions for surface-phenomena sticking problems that complicate the automated handling and release of microobjects. This case study incorporated the results of past work on identifying biologically connotative keywords to find relevant analogies for design, and analogical mapping between the source, biology domain and the target, engineering domain. A biologically connotative word related to "release" is "defend", which was used to identify how proteins are selectively synthesized to defend against infections. The phenomenon involving the interaction between various proteins required to initiate DNA transcription led to a concept where features with different geometries would be used to maximize or minimize surface contact with the microobject as needed. However, this complex interaction mapped into a relatively complex solution compared to one that can be developed based on the abscission principle.

The abscission zone that enables the removal of leaves from plants was mapped into a polypropylene rod that, when slightly melted, was used to pick up and transport a microscrew using an industrial robot gripper that would not otherwise be able to handle the microscrew. The bond between the rod and microscrew was sufficient to enable rundown of the screw, but broke after the screw was fully tightened. Good reproducibility with respect to picking and placing the screws was observed.

The added challenge of physical implementation of the biological strategy in a solution for this case study highlighted the following. Previous work (Shu et al., 2003) conjectured that biological analogies at a scale comparable to the micro assembly scale could be more directly implemented with less need for abstraction. However, the complex and tightly controlled biological processes identified at the micro scale, only one of which was described for this case study, are difficult to emulate. The far simpler strategy of using an intermediate zone that could be broken down, thermally, chemically or mechanically, was more easily implemented, although the concept of an abscission zone was abstracted into the form of polypropylene rods as opposed to being literally implemented.

This case study suggests that further work should focus on the process of abstracting biological principles and entities to implement as practical engineering solutions, as it may not be possible or desirable to completely emulate analogous biological processes.

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