Biomimetics Applied to Centering in Microassembly

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Abstract
This paper describes the application of a biomimetic search method to develop ideas for centering objects in microassembly. Biomimetics involves the imitation of biological phenomena to solve problems. An obstacle to the use of biomimetics in engineering is knowledge of biological phenomena that are relevant to the problem at hand. The method described here starts with an engineering problem, and then systematically searches for analogous biological phenomena using functional keywords. This method is illustrated by finding and using analogies for the problem of positioning and centering objects during microassembly. Relevant phenomena identified involve microtubule organizing centers, photosystems, and retinal ganglion cells.

Keywords:
Design methodology, Microassembly, Positioning

1 INTRODUCTION

Biomimetic design uses biological phenomena to inspire solutions for engineering problems. While many examples of biomimetic design exist, not yet available is a generalized method by which one can find relevant biological analogies for a given engineering problem. Some examples of biomimetic design originated from interesting biological phenomena, and were subsequently developed into engineered products. For example, Velcro hook and loop fasteners were invented after observation of how plant burrs attached to materials such as clothing and animal fur. Other examples of biomimetic design copy fairly obvious examples, e.g., flying machines modeled after birds, underwater machines modeled after fishes, and robotic grippers modeled after the human hand. In other cases, how the biological model was identified and selected is not clear. Therefore, to make biomimetic design more accessible to engineers, required is a generalized method by which one can identify relevant biological analogies for a given engineering problem in an objective and repeatable manner.

Such a method has been introduced in earlier work, and will be summarized here before describing the current problem in microassembly. Next, the results of searching for phenomena relevant to the selected problem will be presented, including the potential strategies and solutions that may be derived from these biological phenomena.

2 BACKGROUND ON BIOMIMETICS

2.1 Related work

Numerous examples of biomimetic design have been documented in various forums. Those described in CIRP Annals include the work of Ueda *et al.,* who developed the concept of Biological Manufacturing Systems (BMS) to deal with unpredictable changes in external and internal environments of manufacturing systems based on biologically inspired ideas [1-3]. Specifically, evolution-based and self-organization models of manufacturing systems were developed that can cope with environmental changes such as system reconfiguration, machine breakdown and unforeseen production requests. Also described are reinforcement learning approaches for the modeling of BMS [3].

2.2 Previous work

A biomimetic search tool was developed that locates in biological knowledge in natural-language format occurrences of keywords describing the engineering problem. While difficulties common to natural-language processing occurred, this approach does not require the tremendous and somewhat subjective task of categorizing all biological phenomena by engineering function. Thus this approach can readily take advantage of the enormous amount of biological knowledge already in natural-language format. A previous application problem involved finding and using biological analogies in design for remanufacture [4-5].

Source of Biological Information

The initial source of biological information, *Life, the Science of Biology* [6], is the reference text for the introductory course in biology at the University of Toronto, and is suitable here for two reasons. First, the book is at a level that is easily understood by those who have little or no background in biology. Second, the book is general and covers several levels of biological organization, from the molecular (e.g., DNA) to the ecosystem level. An electronic copy of the text was obtained and a search tool developed that looks for occurrences of functional words describing the engineering problem within the text. As reported previously, this initial source may not give enough details to inspire a novel solution, but is useful for identifying relevant phenomena that can then be further researched in more advanced sources [4]. More specific texts used to find details on relevant phenomena include those on molecular and cell biology, plant physiology and animal physiology [7-9].

3 PROBLEM DESCRIPTION

The increasing trend towards miniaturization in products and components also affects the associated manufacturing processes and systems [10]. The important role of microassembly in the process chain is described in a recent CIRP keynote paper [11]. Problems relevant to microassembly are identified and include the need for increased positional accuracy, the mechanics of interaction between objects, and the loss of direct hand-eye coordination.

The problems of gripping, moving and releasing microobjects continue to provide challenges and thus motivate novel solutions. Various grippers for microassembly have been proposed and can be categorized as contact and non-contact. Contact grippers are based on working principles including mechanical contact, vacuum, adhesion, electrostatic force and ultrasound. Interestingly, a distributed micromotion system has been described that is based on arrays of small actuators called cilia, which are analogous to their biological counterparts in the human respiratory system [11]. Non-contact grippers have been developed and are based on principles that include optical traps, magnetic fields and electrical fields, and electrostatic grippers, each with specific advantages.

Many of the above gripping techniques were reported to lack the ability to center grasped objects. While mechanical grippers can overcome this disadvantage, problems associated with mechanical grippers include design complexity and unsuitability for clean room environments [12].

The focus of our example problem is then the task of centering, generally for positioning during micro-assembly, and specifically for positioning an object within a gripper. The biomimetic approach is used to identify possible solutions and the solutions are discussed in a manufacturing context.

4 ANALOGIES LOCATED

Searching for the functional keyword “center” in [6] located several phenomena. Matches found to be relevant to centering during microassembly follow.

In the sections below, first provided is the background and context for the phenomenon of interest. Next explained is what strategy each phenomenon uses for the act of centering in the biological system. Finally described is how the strategy can be used to center objects for microassembly.

4.1 Microtubule Organizing Center (MTOC)

Background

The first phenomenon of interest is how the microtubule organizing center (MTOC) centers itself in certain types of cells. First explained are the structure of microtubules and the functions they serve in cells.

Microtubules are minute tubular structures, about 25 nm in diameter and up to several micrometers long. These long hollow cylinders are found in eukaryotic cells (those that contain genetic material within a nucleus) and play roles in cell motion and shape maintenance. Microtubules are dynamic structures, i.e., they are constantly built up and broken down, through polymerization and depolymerization, respectively of molecules of a protein called tubulin. The two different ends of a microtubule are labeled + and –, and tubulin dimers are typically added or removed at the + end. Microtubules provide a rigid internal skeleton for some cells, particularly at cell extensions. Tubule polymerization leads to a rigid structure, whereas tubule depolymerization collapses the rigid structure [6].

Centering Strategy in Biological System

Many microtubules radiate from a region of the cell called the microtubule organizing center (MTOC) as shown in Figure 1. In certain types of cells, the MTOC is strikingly at the center of the cell. It is suspected that the centering mechanism involves extending microtubules that “scout out the cell periphery” [7].

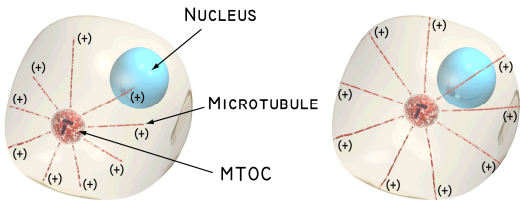

Figure 1: Centering of MTOC by extension of microtubules towards cell boundary. Modified from [7].

Centering Strategy in Microassembly

The above centering strategy is fairly straightforward and thus could be applied directly. For example, extension of same-length spines or spokes from an object would cause it to be centered within a cylindrical or spherical gripping volume. After the object is centered within the gripper, the more precise knowledge of its location will help in accurate placement of the object, after which the centering spines can be removed. Less literal and possibly more practical interpretations of this strategy are presented following description of the remaining two phenomena.

4.2 Photosystems

Background

The next phenomenon of interest is how photosystems in plants focus light energy into the center of an antenna complex to synthesize compounds including glucose in the photosynthetic process.

A chloroplast is a subunit in a plant or algae cell that contains chlorophyll and is where photosynthesis takes place. Within the chloroplast is the thylakoid membrane, embedded in which are chlorophyll and other pigment molecules that are organized in units called photosystems. Each photosystem consists of an antenna complex and a reaction center, and includes about 250 to 400 pigment molecules. Each of the pigment molecules can absorb a photon and enter an excited, unstable-potential-energy state. Rather than returning to the ground state by emitting the absorbed energy as fluorescence, the absorbed energy is passed onto another pigment molecule by resonance energy transfer.

Centering Strategy in Biological System

The direction of energy transfer is from pigments that absorb shorter wavelengths (and higher energies) to pigments that absorb longer wavelengths (and lower energies) of light, until the excitation collected by all pigments in the antenna complex is funneled towards the two pigment molecules that absorb the longest wavelength. These two special chlorophyll molecules occupy what is called the reaction center of the photosystem. The combined excitation boosts an electron in the special chlorophyll molecule into a higher energy state, which is then transferred to an electron-acceptor molecule. This conversion of light energy into chemical energy at the reaction center is used to continue the photosynthetic process [6].

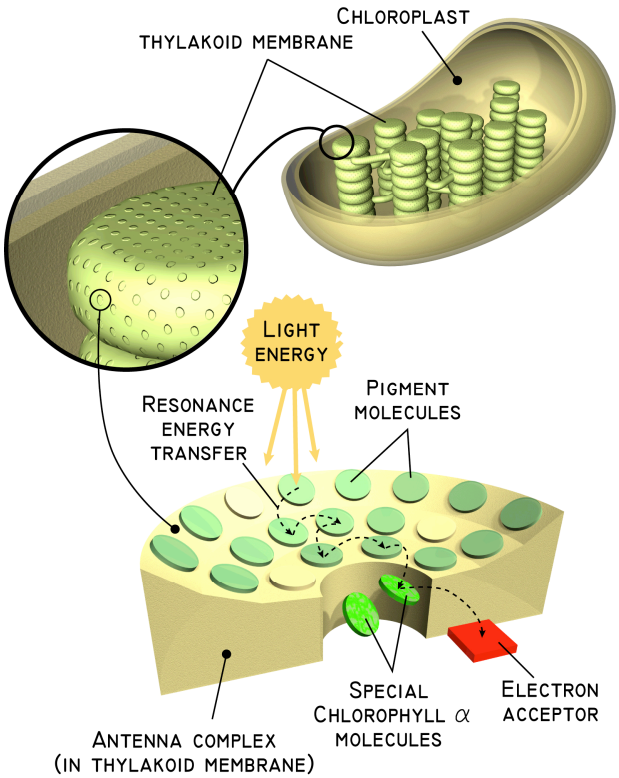

Figure 2: Funneling of light energy to the reaction center of a photosystem. Adapted from [8].

Centering Strategy in Microassembly

One interpretation of this phenomenon is to use a physical funnel, i.e., an object is directed to a center position based on differences in potential energy.

A literal interpretation is to use regions of differing absorption wavelengths (or other property) to focus energy collected by an antenna to effect a reaction, e.g., attraction of object toward a specified location.

This centering strategy can be interpreted in the context of different gripper working principles mentioned in the problem description, e.g., the gradient in property that leads to a centered object can be the strength of the vacuum, electrostatic or magnetic, or adhesive force. The use of electrical fields in biotechnology to separate, trap and classify cells is well known [11]. The idea of using gradients to center an object within a gripper is however new. The concept may even be extended to encompass the interaction between gripper (including object) and the component where the object is to be positioned.

4.3 Retinal Ganglion Cells

Background

The third phenomenon of interest is how retinal ganglion cells sense center versus off-center light stimuli. Retinal ganglion cells integrate responses from photoreceptors to light stimuli that is then communicated to the brain. These cells have circular receptive fields that consist of center and surround regions. An on-center ganglion cell responds most to light on the center area, while an off-center cell responds most to light falling on the surround area.

Figures 3a and 3b compare the responses between on-center and off-center ganglion cells to light stimuli that cover different regions of the receptive field. Note the opposite responses to the small spot of light (second row) and the ring of light (fourth row). Of particular interest however, is the relative similarity between the responses to total darkness (first row) and large spot of light covering entire receptive field (third row).

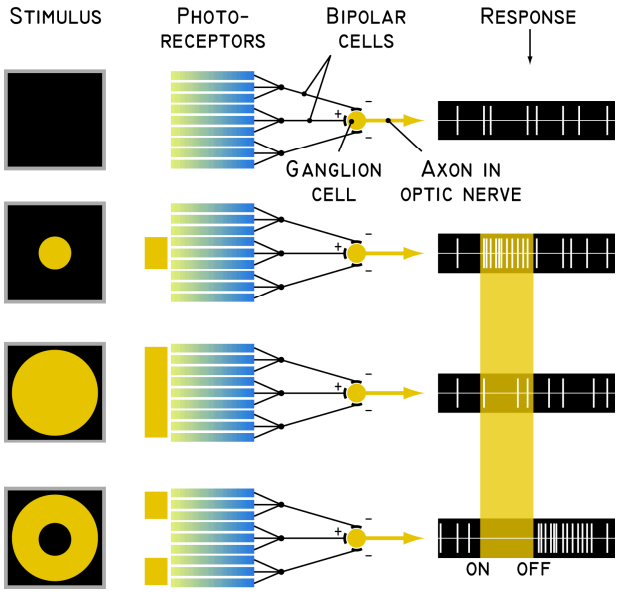

Figure 3a: On-center responses to light stimuli.

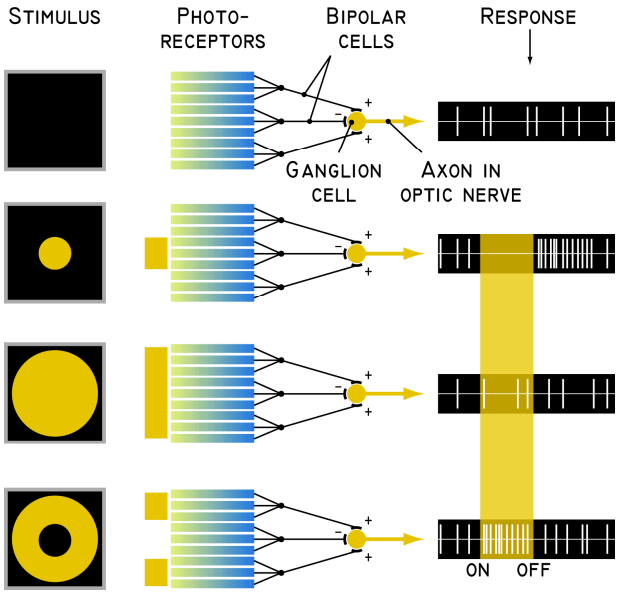

Figure 3b: Off-center responses to light stimuli. Adapted from [6] and [9].

Centering Strategy in Biological System

One would expect that the response to a large spot of light that covers both the center and the surround areas of the receptive field might be a superposition of the responses to the center-only and surround-only light stimuli. This however is not true, due to the opposing effect of light stimulus to the surround versus center. Specifically, direct input to bipolar cells from overlying receptors opposes indirect input to bipolar cells through the horizontal cell network [9].

Centering Strategy in Microassembly

This phenomenon may be directly used for detecting whether an object is centered or not, e.g., by shining a light past it onto a sensor that distinguishes whether a shadow is cast in the center by the object, and to effect a response if it is not. This however requires high-resolution optical measurement techniques to be applied close to the gripper and object [11].

Also of possible use is the strategy of having off-center stimuli impose an opposing effect to on-center stimuli. For example, using positive pressure in the surround versus a vacuum in the center to position and

stabilize an object in the center, or reject it from the gripper for a vacuum-based gripper. Other possible implementations include opposite charge between center and surround, repulsion versus adhesion between center and surround, etc.

5 CONCEPT DEVELOPMENT

To further illustrate the use of the biomimetic approach, we will further develop concepts based on the first phenomenon identified, MTOC-centering.

A possible implementation of the MTOC-centering strategy of extending temporary spines may be accomplished using a substance like CO_2-ice, shown in Figure 4a. After positioning, the temperature is increased and the ice surrounding the part sublimates.

A more abstract interpretation could be to have the spines extend from the gripper instead of the object. After positioning the gripper close to the part, the spines extending from the gripper will push the part into a known position and handling can be carried out. A possible configuration is a flat gripper with a number of flaps as shown in Figure 4b. The gripper can be fabricated with a base plate of elastic material (metal) and a plate of shape memory alloy (SMA) e.g. Ni-Ti. The SMA can be configured to seek a specific position when heated to a specific temperature. The elastic material will then return the flaps to the pre-heated position when the temperature is decreased.

Mechanical grippers, e.g., as described in [12], are usually constructed with two opposing arms or fingers. The use of more than two independently controlled fingers makes it possible to accurately position even non-symmetric objects within the gripper.

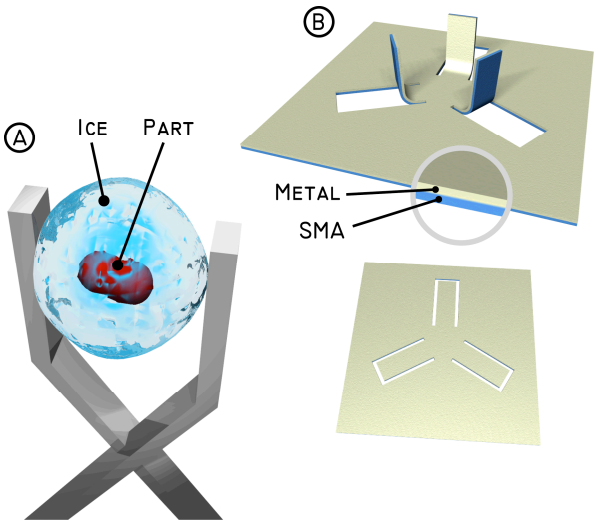

Figure 4: Possible implementations of MTOC-centering.

6 SUMMARY

This paper describes the application of a biomimetic search method to develop ideas on how to center objects in microassembly. By searching for the functional keyword “center” in a computer-searchable biology text, three relevant phenomena identified are microtubule organizing centers, photosystems, and retinal ganglion cells. The centering strategies used in the above biological systems that may be useful in microassembly are: extending spines from the object to be centered to scout the boundaries of the volume within which the centering occurs, using a gradient in property (e.g., wavelength absorption) to direct collected energy to a center and, using opposing forces between center and off-center regions.

Worth noting is that previous applications of the biomimetic search identified biological analogies at various levels of organization, from molecular to ecosystem [13]. Thus abstraction that involves scaling was often required to apply the analogy to the problem.

While no attempt was made to limit the biological phenomena for the microassembly problem to the cellular level, it may be possible to more directly implement some of the solutions from similar scales in biological systems with less need for abstraction.

This paper has demonstrated that the search for functional keywords through biological knowledge in natural-language format is capable of locating relevant biological phenomena that has the potential to inspire novel solutions for problems in microassembly.

7 ACKNOWLEDGMENTS

Gratefully acknowledged are: O. del Rio, M. Park, and A. Shaw of the University of Toronto and the financial support of Natural Sciences and Engineering Research Council of Canada towards developing the biomimetic search tool; T. Nissen of the Technical University of Denmark for drawing all of the figures in this paper, and partial support of L. Shu’s sabbatical stay at Technical University of Denmark from COWIfonden.

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