Turning Machines - DNA implementation of simple molecular robotics

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June 2024

Abstract

Molecular robotics considers the problem of designing molecular-scale structures that sense, move and carry out a variety of tasks with nanoscale precision. The three main challenges are (i) theory - defining a model, characterizing its abilities, setting goals and tasks, (ii) implementing the model - designing the robot structure - placing specific molecular components where you want them to create the desired structure, and (iii) actuation of the molecular-scale robot to perform desired tasks. In recent years there have been many advances in molecular self-assembly using DNA nanotechnology, in particular we can reliably form nanoscale structures using a technique called DNA Origami. The type of molecular robots we have seen emerge in the field thus far include DNA Walkers, which exploit DNA complementarity to walk along a track, and reconfigurable DNA structures that can change their structure when detecting a chemical input signal (e.g. changes in salt concentration, or the addition of a triggering DNA strand). However, both of these examples are limited in their computational ability. Walkers rely on specifically designed tracks, which limits the contexts in which they can perform computation (e.g. sorting molecular cargo on a 2D surface), while reconfigurable DNA structures are capable of functioning in solution in isolation but are typically limited to a small set of states (e.g. binary switches) or have a lack of reversibility.

Our goal is to propose and implement a novel model for molecular robotics. We began with the Turning Machine model, which consists of a line of simple connected robot units: initially, each robot encodes an integer specifying the number of 60° rotations to perform to compute, or fold the entire line into, a target shape. These individual arm rotations occur asynchronously and uniformly at random until the target shape has been reached. Simplicity was the key design principle in mind when developing the model in order for it to be feasible to implement using DNA. However, even with simplicity in mind during the model development, Turning Machines have proven difficult to implement fully. Our current design is both modular and scalable, exploits geometry of double-layered DNA origami to achieve the desired achieve the desired turns, and is capable of reconfiguring between target shapes. Our ultimate goal is to provide a DNA-based molecular robot that folds a variety of shapes, can fold any of these shapes into any other, and do so via sensing of environmental signals (such as trigger DNA strands) and to control these processes via computation.