Arm Module

Robotic Arm Module by Mark Kershishnik

Figure 1: Outline of graphical synthesis goal

Figure 2: Final construction

Robot Arm Module:

The arm mechanism is a six bar linkage with four binary links and two ternary links. The goal of the mechanism is to move the claw from the extended position to the contracted position so that the bottle is delivered in the correct orientation for pick up and for launch. The mechanism can cross over into an unwanted geometry, but this is prevented by using hard stops attached to the claw attachment link and at the ground link. The mechanism is to be driven by an electric motor in two directions and as such requires some slightly more sophisticated motion control. Ideally, the mechanism would be improved by reconfiguration to employ the Grashoff condition such that a full rotation of the input link provides the desired motion and also returns the linkage to the initial position, however the geometry of the entire machine would not allow for this.

Synthesis of the Arm Module motion:

The arm mechanism was originally conceptualized as a four-bar linkage. When the preliminary designs of the launcher module were delivered, it was clear that it would be advantageous to add an element of controlling the orientation of the item to be "recycled," and a simple four bar does not deliver a complex enough motion to achieve this. Hence I began work on modifying a four-bar linkage, knowing that the topology must include four binary links and two ternary links for a one degree of freedom motion (among several other configurations as outlined in Norton's Design of Machinery, see Norton Table 2-2). The mechanism can also be analyzed as a composite of a four-bar subchain and a five-bar subchain. The mechanism was contrived mainly by graphical synthesis using a home-made compass, which allowed simultaneous dimensional synthesis. Several heuristics were discovered in the process regarding the geometry of motion and they will be discussed below.

It is clear that the motion can be divided into two general branches: the movement of the main four-bar sub-chain to bring the claw link up to the final position, and the rotation of the claw link about the end of the long arm link for proper orientation. The first heuristic that was inferred was that the claw link simply needs to be rotated about one point and this was accomplished using the idea of a third class lever. The second heuristic relationship discovered when the driving link (lower link attached to ground) was converted to a ternary link. It was quickly realized that if the driver link is simply coupled to the claw link (to create the lever action), the only synthesis that needs to be done is to analyze the distances in the beginning and end positions and ensuring that the linkage can go through the desired range of motion. At this point, a preliminary SolidWorks model was drawn up and dimensions of the claw and coupler link were tuned to create the desired output.

SolidWorks Modeling

To fine tune the motion, the mechanism was drawn up in a SolidWorks assembly. The motion was analyzed mostly qualitatively for smoothness and avoidance of unwanted toggles amongst other things. Two improvements were made to the design this way, the first including sizing the long coupler link to produce a desirable amount of claw link rotation between design positions. The second improvement was not realized until after preparing to construct a real physical model of the linkage. The driver link was originally designed to be a simple 'L' shape (See Figure 3 below), however this would lead to problems in assembly as the link would run into the structure holding the other links. A solution to this problem was not difficult to come by and proved to be an elegant fix (See Figure 4).
A model of the final linkage design (as seen in the second prototype) can be seen below in Figure 5 in three positions to demonstrate the motion from start to finish.
Analysis of the Factors of Merit

The toggle positions for this linkage are beyond the range of desired motion so mechanical hard stops were put into place on both the claw link (since there is a lot of real estate on that link) and the ground. Since the motor has to drive a load and a potentially heavy linkage against gravity throughout most of the range of motion, one of the most important factors to account for is the mechanical advantage of the whole linkage. For simplicity, the mechanical advantage of the four-bar subchain was calculated throughout the range of motion (roughly 245 degrees) and it was assumed that this would give a good estimate of the mechanical advantage of the full mechanism as the four-bar subchain does the majority of the heaving lifting. A plot of the mechanical advantage of the linkage of the range of motion can be seen below in Figure 6. Clearly the linkage goes through a position where the mechanical advantage is infinite meaning that the coupler link and the ground link become parallel to one another at the point of infinite MA. The transmission angle (i.e. the angle between the coupler link and the arm link) is also plotted to demonstrate the quality of the linkage as good practice dictates that the couple angle should not fall below 40 degrees throughout the range of motion (see Figure 7). Avid Matlab users will recognize that the plots were made using Matlab!
It is worth mentioning that the mechanical advantage of the linkage does indeed go below unity throughout the latter half of the motion, and this is primarily due to the fact that the load is calculated to be at a point that is substantially far away from the point of rotation of the driven ("long arm") link. It was anticipated that the motor would be able to handle a lower mechanical advantage as long as the MA in the starting position is not below unity, which it is not. Luckily, DC motors generally follow linear Torque vs. Speed relationship, so any slowing of the motor due to additional load will only improve its torque. As such, the linkage design was not pursued any farther and construction was begun.

Construction
The mechanism was constructed mostly out of wood and roller bearings were scavenged from a previous project to construct high quality joints. There were few issues in the construction of the mechanism, but unforeseen design challenges were dealt with on a case by case basis with the constraints of what was available at the moment. For example, perfect alignment of the mechanism so that all of the links remain parallel to each other through the entire range of motion with loads proved to be rather difficult. It is desirable to use joints that are supported in double shear as opposed to cantilevered, however this is not always possible and the only solution to this problem was to ensure that resilient shafts (hardened steel) were used and that the bearings aligned and set carefully as well as fastened robustly. I was able to improve the mechanism for the second prototype so that the driver link was supported in double shear, however other links were kept as light as possible and constructed carefully.

The tools used in the production of the entire mechanism include:

**Woodworking Tools:**
- Table Saw
- Miter Saw
- Band Saw
- Hand Saw
- Drill Press
- Router
- Belt Sander
- Finishing Hand Tools

**Machining Tools:**
- Band Saw (cutting steel and aluminum shafts)
- Lathe
- Milling Machine
- Finishing Hand Tools

3-D printing was also used to produce a spline to transfer power from the motor to the driver link, and a 1/8" x 1/8" key was milled to lock the motor shaft in place in the spline. A SolidWorks model of the spline can be seen below (Figure 8), and the final constructed linkage can be seen on the main page of this Wiki article.

Figure 8: Mechanical spline to transmit rotary power from motor to driver link.

**Persisting Issues**
One major issue did not crop up until the entire mechanism was fully assembled and motor testing began. Within running a few cycles, the rapid action of the motor wore in the key way of the spline and introduced a significant amount of play ("slop"). This led to some uncontrolled motion on the descent of the arm back into the lowered position during which gravitational loads become a problem. If the motor is driven while the arm is falling, this uncontrolled motion can cause the arm to slam into the hard-stops, and although the linkage was never damaged, it is not unlikely that such a violent cyclic loading would quickly wear on the mechanism. The proposed solution to this problem is to introduce some damping into the motion to slow its descent which could be easily produced by adding friction into the joints. However, increased friction may overload the motor beyond acceptable limits when driving the linkage upwards (against gravity) and as such, the ideal solution would be to introduce one-way damping into the system so that it is only damped on the descent back into the lowered position. Of course, such a mechanism might be difficult to design and construct in a short amount of time and expensive to simply buy. Other than the fact that the linkage was not perfectly aligned and had difficulties with its descent, it served its designed purpose well.

Lessons Learned

Overall, this project has demonstrated that the ubiquitous four-bar linkage is indeed a very powerful mechanism due to the myriad ways it can be exploited in its geometry to perform simple tasks efficiently. Increasing the complexity of linkages can help one design complicated motion paths and the six-bar linkage made control of the orientation of the object to be transported possible. Nonetheless, it is realized that even though many potential linkages were drawn up on paper, it would have been advantageous to add two or three more designs to the table for testing with physical models for a comparison. Adding more design iterations could have illuminated even more overhead. Probably the most difficult problem to deal with was designing the linkage so that it could be aligned to a higher degree, however the performance of the available tools may have been a limiting factor. In the end, much has been learned from this project and I will continue to design and analyze mechanisms whenever and wherever they may be needed.