

# Teaching mechanism design

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## Abstract

This paper describes a teaching exercise which demonstrates the design and analysis of a simple mechanism used to pour beer from a bottle into a glass. Video frame grabs, of the manual pouring process, provide a motion template by which students synthesise a six-bar linkage which replicates the task. The teaching method along with typical outcomes of the project are presented.

## 1 Introduction

Students, in undergraduate Mechanical Engineering courses, are typically introduced to the study of machine dynamics through an introductory unit in Dynamics. The fundamental physics of motion are explained as the student works through a large number of problems contained in one of the acknowledged first-year textbooks [Meriam & Kraige 1997].

A second subsequent course in machine dynamics requires an alternative approach to the rote learning to which students have become accustomed in their first year. A group project teaching method, based on mechanism design, is discussed in this paper along with a sample assignment conducted in 2005 at Queensland University of Technology. This approach to teaching is not new, as it is championed in a few US Universities [Erdman 1991], [Norton 2004]. However the approach has not been adopted, to my knowledge, in Australian universities.

## 2 Concepts which need to be taught

The concepts which must be re-enforced following the students' introduction to dynamics are the properties of general plane motion: i) position, velocity and acceleration of points ii) orientation, angular velocity and acceleration of rigid bodies. In addition students need to be taught how these path properties may be measured and generated using simple planar mechanisms.

Synthesis of motion using mechanically traced paths,

created by closed mechanisms, is a topic which grew in the nineteenth century. [Hunt 1978]. However the study of classical kinematics is greatly assisted by computer numerical analysis and graphics. Such computational tools as MATLAB are invaluable, in that they allow rapid analysis of the mechanism's motion. Methodical and extensive optimisation of the basic design, through many iterations, is possible using modern computational tools.

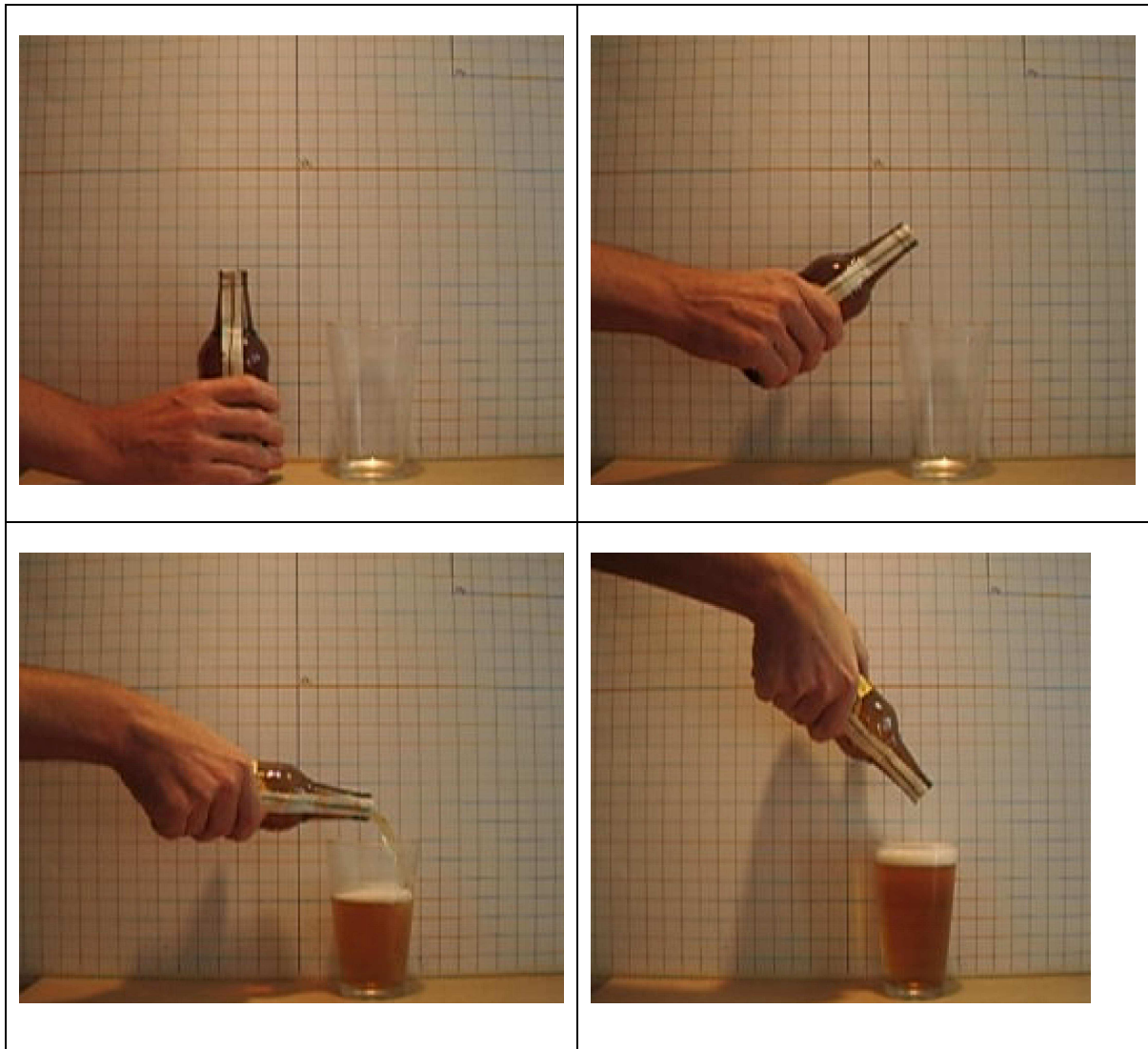
Students are often amazed at the complexity of motion which can be generated by simple mechanisms. An introductory course in mechanism design needs to illuminate both the strengths and limitations of simple single-degree of freedom mechanisms and open-loop control. This provides a starting point for a future course in robotics where multi-degree of freedom mechanisms and closed-loop servomotor drives control the path of the mechanism under the guidance of computer numerical control.

## 3 Class organisation

Class size, for the exercise discussed in this paper was 160 students. They were divided into groups of four, with students choosing their own groups. Available tuition time was 3hrs per week, comprising 1.5 hours lecture (160 students) and 1.5 hours for tutorial/computer laboratory sessions (40 students). The assignment was structured so that the student groups could make continuous progress throughout the semester, at the same pace as the lecture material was delivered. Practical content of the course was delivered through project groups manufacturing their mechanism, at home, and demonstrating their device to their colleagues at the end of semester.

## 4 Project specification

A video of beer being poured, by hand, into a glass against a background grid was given to the students. Both the bottle and glass start at prescribed positions as shown in figure 1a. The path shown on the video was used as a template, which if followed, will result in the beer being



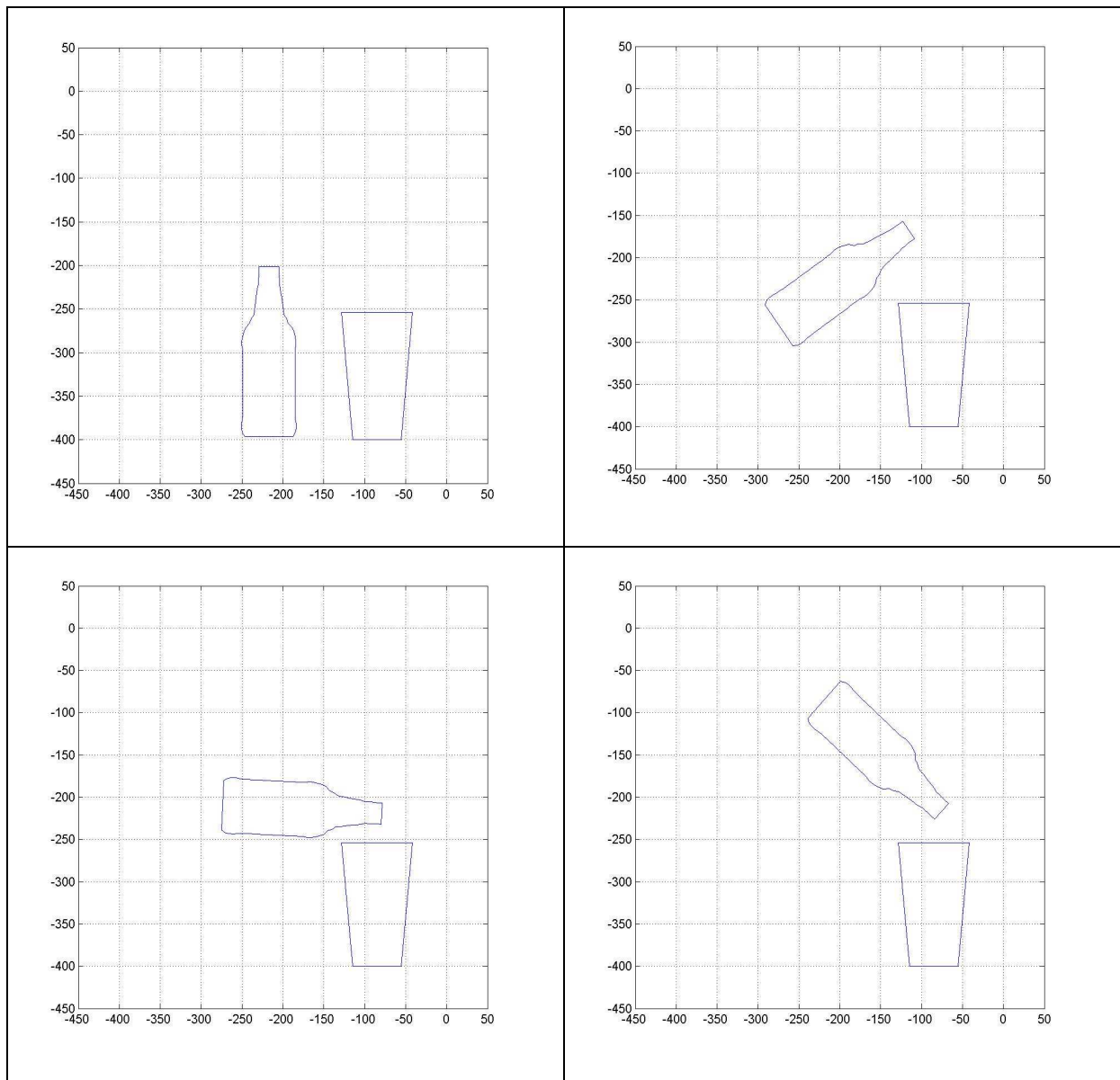
**Figure 1** Four frames from the video sequence of 136 frames total, showing the prescribed motion. (see video clip BEER\_POUR4.mpg)

transferred into the glass without spillage or froth overflow. Students were required to design a mechanism, *driven by one motor*, which would move the bottle through a similar path. The final proviso was that, on completion of the pouring operation, the bottle must return to its original starting position *without reversing the motor*.

Frothy liquids are difficult to pour. In order to successfully complete the task it is important to, not only follow the path shown in the video, but also adhere to the correct timing. Velocity and accelerations are also important properties of the required motion. A successful pouring operation is one in which the liquid flow-rate is controlled and the drop height is minimised. Since tilting the glass was not permitted, minimising the drop height is most easily accomplished if the fluid stream is directed along the side of the glass, as shown in Figure 1c.

## 5 Prescribed path

Manual pouring operation shown in figure 1, was originally filmed at 30 frames per second against a 20mm spaced grid, with a nominal origin located at the top right hand corner of the frame. Every fifth frame was imported into MATLAB and a total of 136 frames spanning approximately 20 seconds defined the motion. Using MATLAB, students were able to identify i) the origin, ii) the position of the bottle tip and angle of the centre line of the bottle using a pixel count, which could be calibrated to distance (millimetres) via the known grid size. Accurate calibration of images and measurement of pose is the subject of much current research in visual servoing of robots. A first exposure to the problem through this simple exercise is a particularly valuable learning experience.



**Figure 2** Four frames from the computer graphical animation of the manually produced motion. (see video clip `bottle_animation.mpg`)

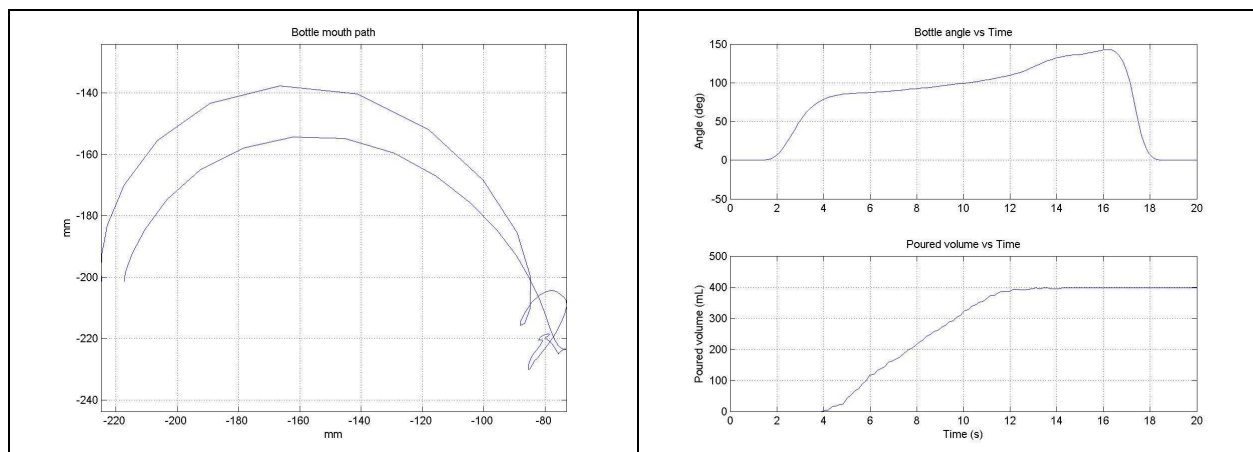
The next stage of motion analysis was to create a computer animation of the motion. Figure 2 shows four frames of the continuous sequence created using MATLAB. Figure 3a shows a Cartesian plot of the displacement of the bottle tip during the manual pouring operation. Also shown in figure 3b are the change in orientation angle of the bottle and the poured volume plotted against time. The poured volume was estimated by noting the liquid level in the glass throughout the sequence.

Plots of angular velocity and acceleration as well as speed and acceleration of the tip of the bottle were generated by successive numerical differentiations of the displacements as shown in figures 4.

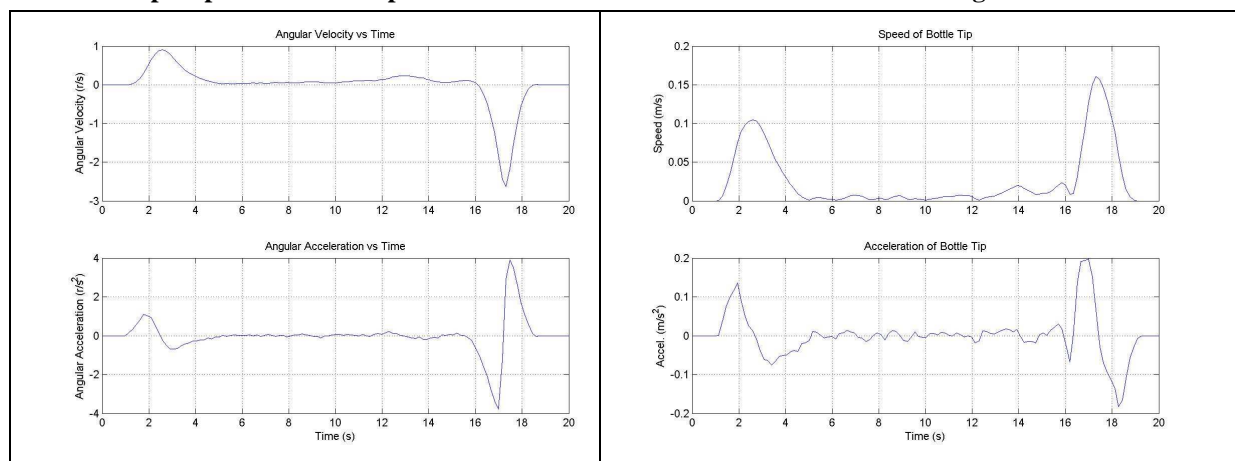
## 6 Carrier linkage synthesis

Generation of motion such as that displayed in the video is a classical problem of mechanism synthesis. A design process is explained in various texts eg. [Norton 2004], [Erdman 2001] and the entire class can be guided through the problem via a series of structured lectures.

Figure 5 shows how a four-bar mechanism, capable of moving the bottle through the three prescribed locations, can be synthesised. These three prescribed locations are strategically chosen, from the 136 possible locations identified in the movie, to represent the required task. The designer also needs to make a choice as to where the connections (the moving pivots) should be attached to the bottle. This choice is predicated by the type of holder in which the bottle sits.



**Figure 3** Bottle tip displacements and poured volume vs time derived from the 136 frame grabs of the video.



**Figure 4** Records of the path derivatives of the bottle motion, derived from the 136 frame grabs of the video.

The three bottle locations shown in figure 5 correspond approximately to figure 1 frames 1(a) to 1(c). At each prescribed location the upper (red) and lower (green) moving pivot point, attached to the bottle-holder are shown. Centres of the moving-pivot circles are shown connected to their respective moving-pivot at the start of the motion. A (black) triangle coupler link of the four-bar mechanism is shown in its three locations, along with the coupler curve of the tracer point (bottle tip) shown as a solid red line.

## 7 Optimisation

There are an infinite number of four-bar linkages which can do the job, depending on :

- i) which three locations, out of 136 frames available, are used in the prescribed path,
- ii) where the designer decides to place the moving pivots relative to the bottle.

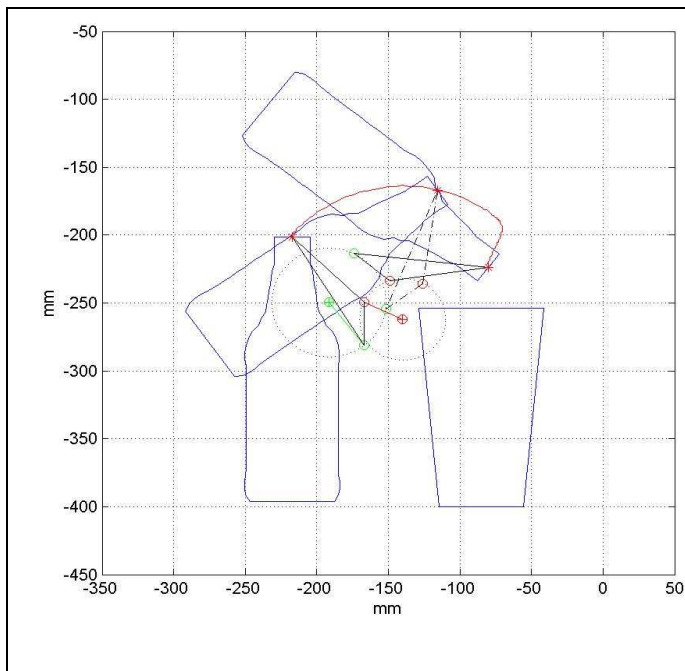
Super-abundance of solutions allows for optimisation of the link lengths of the four-bar carrier linkage. A check on the accuracy of the synthesised path can be made by superimposing a plot of the mechanically generated path over the path obtained from the video data, as shown in figure 6. If the synthesis has been correctly completed then the two paths should intersect three times. The

student needs to take care that all three of the prescribed locations lie on the same circuit of the four-bar mechanism. If this is not the case then the curves will intersect fewer than three times.

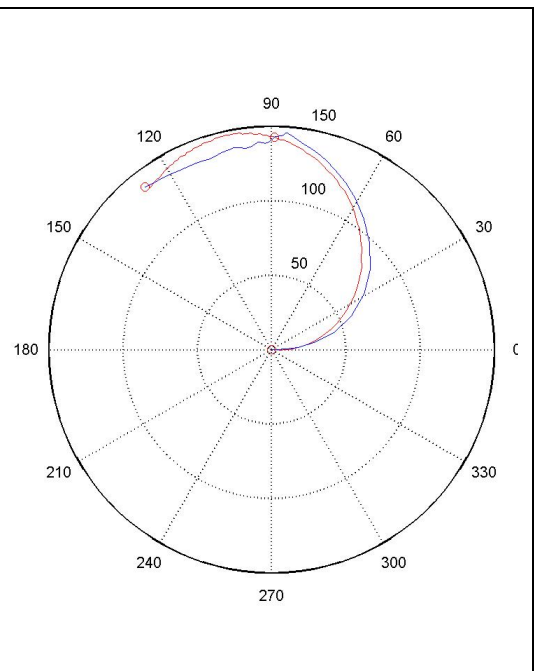
Minimisation of error between the generated and desired path is one criteria which can be used to optimise the dimensions of the four-bar carrier linkage.

## 8 Driving dyad synthesis

The basic four-bar carrier-linkage is augmented with an addition two links, with the input link (crank) capable of full 360 degree rotation. This “dyad” is synthesised to limit the motion of the carrier four-bar to lie exclusively between locations 1 and 3 shown in figure 5. As the input link rotates through its full rotation, the bottle moves from its start location, to the pouring location via a prescribed mid location and returns to the start along the same path, without reversing the motor. In this project the crank was driven by a geared DC electric motor, whose speed could be regulated by adjusting the supply voltage from the power supply. In this way the students were able to control, by eye, the timing of the motion to best achieve the pouring operation.



**Figure 5 Three prescribed locations of the bottle are used to synthesise a four-bar mechanism which carries the bottle**



**Figure 6 Superposition of the actual (red) and desired (blue) paths of the bottle. Angle on the polar plot represents the orientation of the bottle relative to vertical. Radius on the plot represents the magnitude of the distance of the bottle tip from its start position.**

Figure 7 shows the kinematic diagram of a complete six-bar mechanism created by one of the student groups. This figure contains four frames of a computer animation of the generated motion. The carrier four-bar is shown with blue links and a black coupler triangle. Driving dyad-pair is shown in magenta. From this animation the students were able to generate plots of the actual path of the both and its time derivatives for their mechanism along with predictions of the forces and motor-torque required drive the mechanism throughout its journey.

## 9 Manufacture and testing

Student groups were required to manufacture their own mechanism and to demonstrate their work to the assembled class. All forty groups were able to muster a final response, demonstrating varying degrees of success in pouring water from a beer bottle. The key factors in determining success were:

*i) Understanding of the theory of mechanism synthesis:* Poorer groups fudged the problem by shifting the relative starting positions of the bottle and the glass from those prescribed in the video. The other problem which students did not fully appreciate was the fact that even though they synthesised the mechanism using the approved technique, not all of the three prescribed locations lay on the same circuit of the mechanism. Only two of the three prescribed locations were accessible on the one circuit. To access the

third prescribed location the mechanism would need to be dis-assembled; a clearly unacceptable proposition.

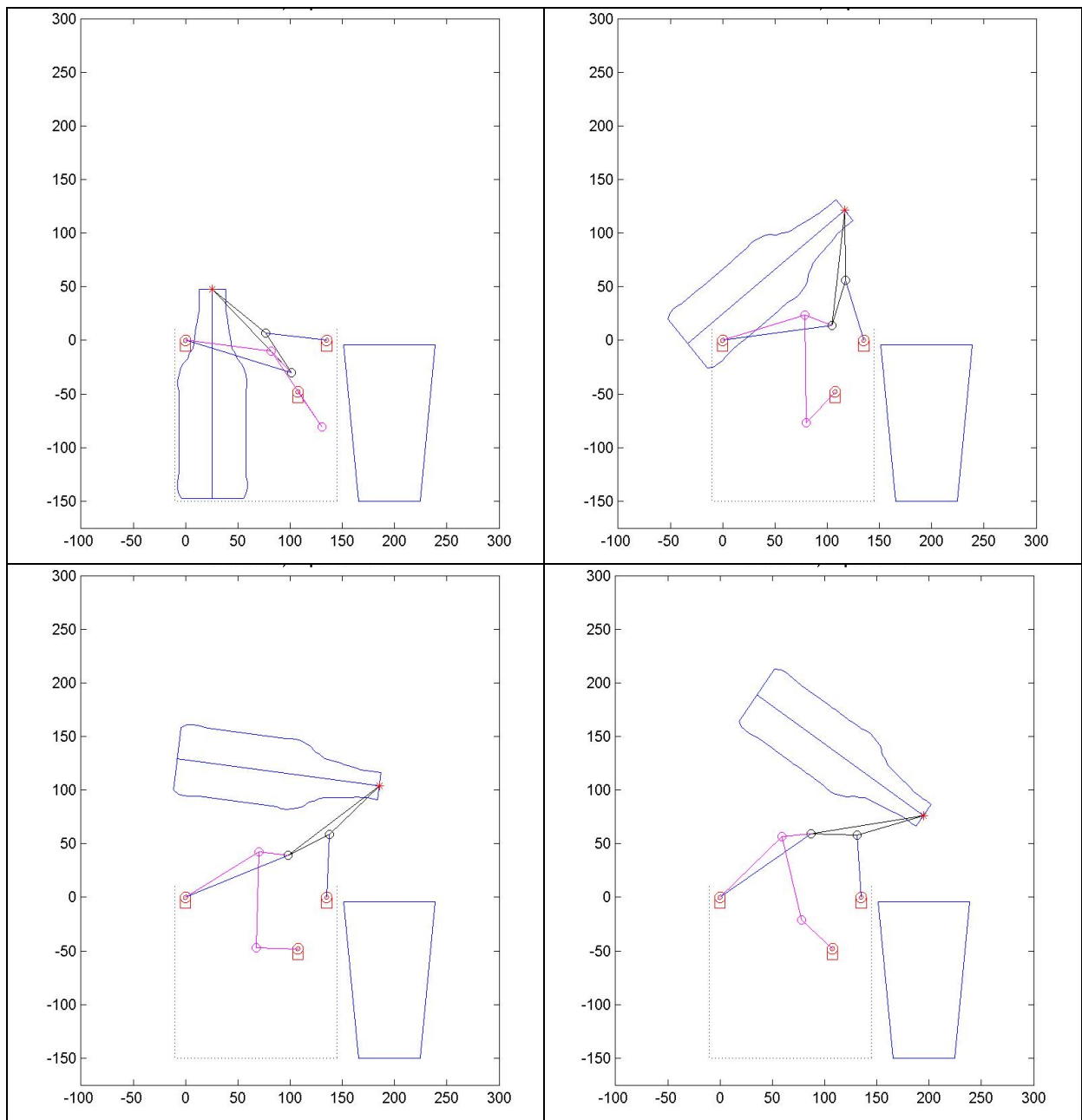
*ii) Mechanism motion analysis:* Understanding of the concept of mechanical advantage and its relationship to the “transmission angle” of the mechanism proved the difference between those designs which could be successfully driven without drawing excessive current.

*iii) Speed control of the input crank:* The most easily controlled mechanisms were those which were driven by optimally geared, low power consumption electric motors.

*iv) Layout:* Students who used a pair of parallel mechanisms, with the bottle swinging between them, had greater success. Their mechanisms were torsionally stiffer and joints less prone to bind due to deformation of the members.

*v) Choice of materials and skill in manufacture:* Most students used materials typically available at a hardware store (plywood and nuts and bolts) and simple hand tools for manufacture. Some students who had advanced technical skills and access to machine tools were able to demonstrate their value in producing a superior quality mechanism.

*vi) Group dynamics:* Well organised groups who implemented a process of internal checking of the work of its individual members were most successful. This was most obvious in their written reports on the project which read seamlessly and logically throughout. A group of non-communicating individuals was a recipe for disaster !



**Figure 7** Four frames from the computer animation of the bottle moving through its path generated by the six-bar linkage. (see video clip `six_bar_animation.mpg`) **Figure 8** is the physical realisation of the design.

## 10 Results

The three best groups went on to test their mechanisms in pouring beer from a bottle. Figure 8 shows a completed mechanism whose motion is animated in figure 7. The students realised the task in a very compact, precisely manufactured package. Unfortunately the mechanism did not accurately generate the motion prescribed in the video of the manual pouring operation. The relative starting position between the bottle and the glass (figure 8a) was wider than prescribed and the drop height (figure 8b) was too large. Also, in this mechanism it was also not possible to finely enough control the timing of the motion through speed control of the motion. This resulted in excessive

bottle velocity and accelerations occurring just as pouring commenced. The flow was too violent and beer spilled over the side of the glass as well as generating an excess of froth.

Figure 9 shows, in plan view, a mechanism which reasonably accurately followed the prescribed path. The students used cheap, readily available materials. They also demonstrated a good deal of skill in the manufacture of the mechanism in spite of the fact that they only used simple hand tools. A pair of parallel linkages was used to overcome the problem of lack of torsional stiffness inherent in the materials. Failure to pour beer without

froth overflow was due to the fact that the motor was geared down excessively. The rate of pour was too slow, causing a thin stream to fall to the bottom of the glass, creating excess froth.

The mechanism shown in figure 10, was elegantly manufactured and most faithfully generated the required path. These students designed their own speed controller and were able to control the rate of pour so that the stream ran down the side of the glass, as shown in figure 10b. The result was an almost perfect pour.

## **Conclusion**

The project was initially poorly received because it was considered by the class to be an impossible task. A fair degree of scepticism remained until the first working mechanism (Figure 9) was demonstrated only two weeks before the hand-in date.

The major difficulty in implementing the project was in being able to resource and tutor the activities of 160 students. Creation of groups, containing four students, alleviates this problem but also causes some negative outcomes. Most groups tended to divide the project into subtasks which became the sole responsibility of one individual in the group. The synergies possible from group learning were not fully exploited.

Considerable demands were placed on the students' ability to source materials and manufacture a working mechanism. Most groups did not fully appreciate this difficulty until too late. Only a few groups exploited the assistance of technical staff who were available to advise them on manufacture.

Success of the project lay in the surprise that the task was, in fact, feasible and that a practical result could be achieved through a rigorous implementation of concepts and skills taught in the lectures and tutorials.

## **Acknowledgements**

The author would like to acknowledge the fine work carried out by the students of the Queensland University of Technology, MMB212 Mechanics 2 class of 2005. This was a very demanding assignment. Cheers !

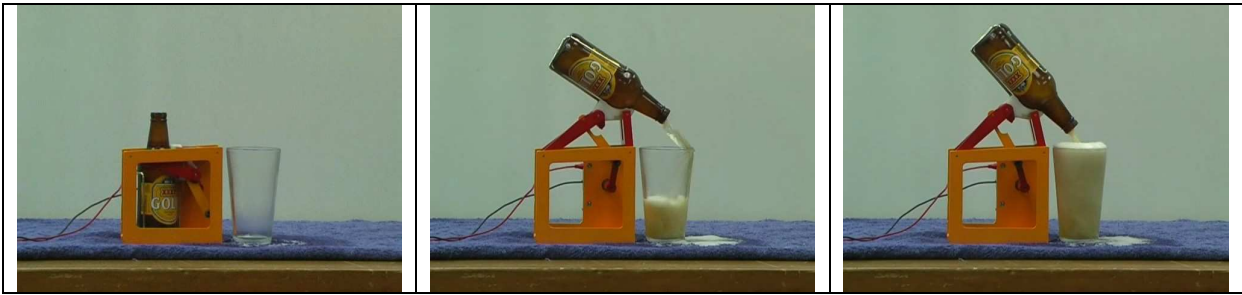
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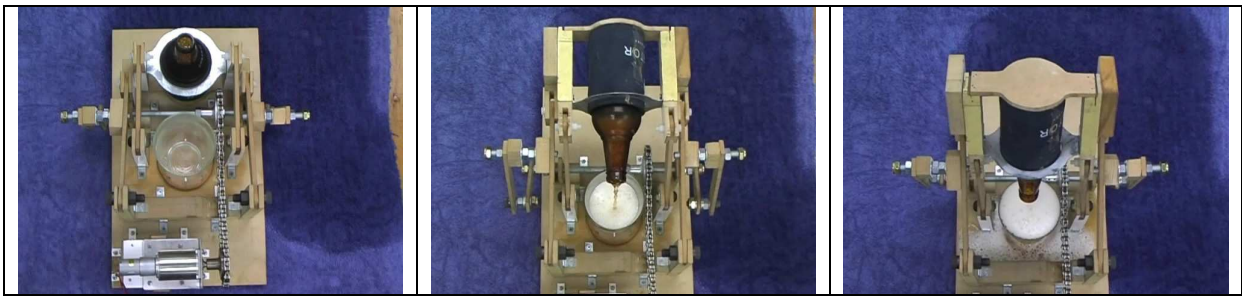
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**Figure 8 Mechanism designed by Norzaki Mizan, Cong Yew Chua, Mohd Jali, and Matthew Mcinnes. (see video clip Group29\_withbeer.mpg)**



**Figure 9 Mechanism designed by Gavin Shaw, Rizki Ramadhani, Paulinus Bimastianto and Andy Chen (see video clip Group31\_withbeer.mpg)**



**Figure 10 Mechanism designed by Perry Kapper, David Lowe, David Benham and Bradley Lewis. (see video clip Group14\_withbeer.mpg)**