Optimizing Energy Efficient Trajectories for Pan Flipping

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Introduction


Recently, there has been a growing robotic cooking industry as shown by companies like Spyce and Dexai Robotics. Dynamic manipulation of food such as pan flipping is still to be developed. Tossing food in pans allows for more efficient cooking, even coating, and easier clean up. It also can be useful for cooking larger, less-granular objects such as pancakes or hamburgers.

Objectives: Identify which variables are critical for efficient and accurate pan flipping.
Determine the tradeoff between energy efficiency versus the starting arm configuration.

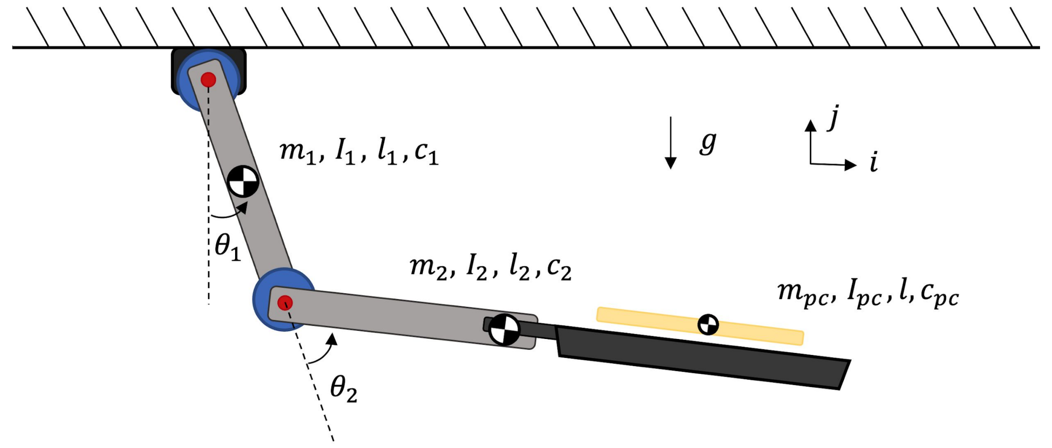
Hypotheses: The flip will be more sensitive to the elbow rather than the shoulder joint.
A more extended arm configuration will result in a higher energetic cost.

Simulation Methods

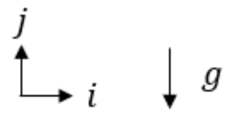
Setup: MATLAB Hybrid Simulation

Arm: 2 DoF open kinematic chain simulating a shoulder, elbow and a fixed wrist. Pan is modeled as a flat segment of the elbow link.

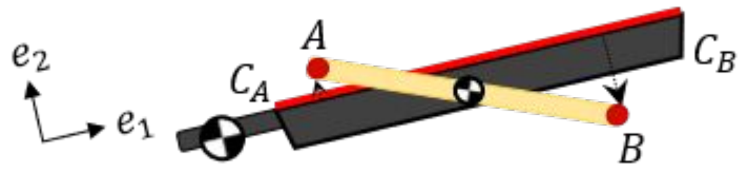
Food ("Pancake"): Floating 2D Rigid Body



Contact Model:



Spring Damper Model of 2 points (pancake) vs a line (pan)



Calculates and applies a Force and Torque around the pancake's center of mass. Assumes the force on the arm is negligible.

Control Strategy:

$t \leq t_{ctrl}$ — *Torque Controller* using 3 Bézier control points for each motor.

$t > t_{ctrl}$ — *Pancake Tracking Controller* which tracks the "x" position of the pancake after it leaves the pan and keeps the pan parallel to the ground.

Optimization: MATLAB's fmincon

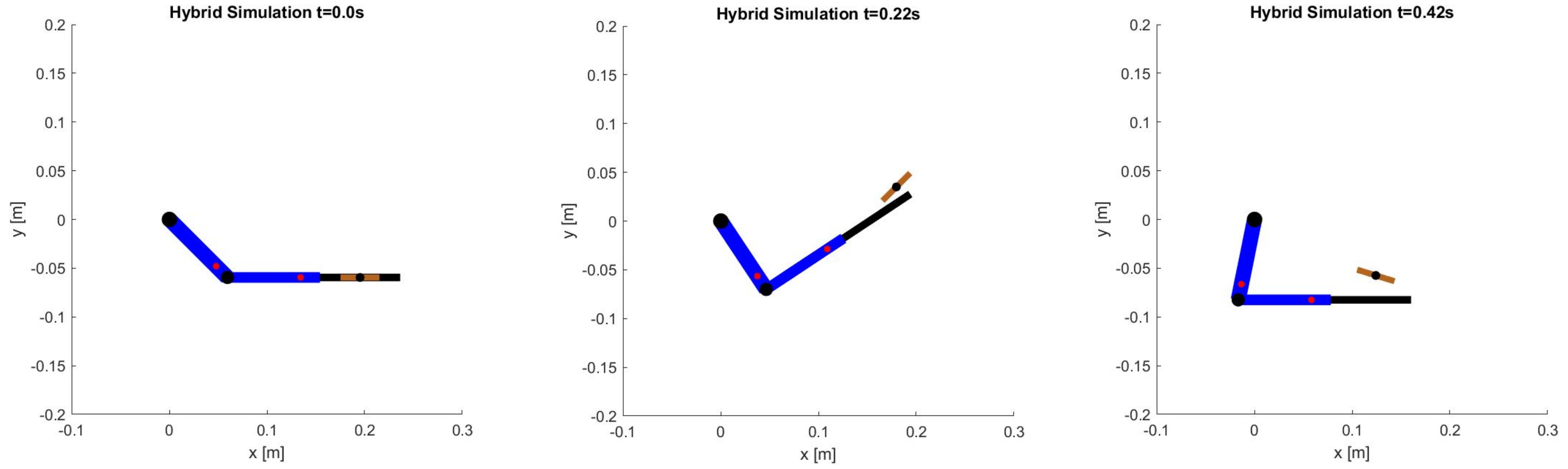
Objective: Minimize the energy used to flip the pancake → $\min_{T_1, T_2} \; C(X) = \int_0^{t_{ctrl}} (\tau_1^2 + \tau_2^2)$

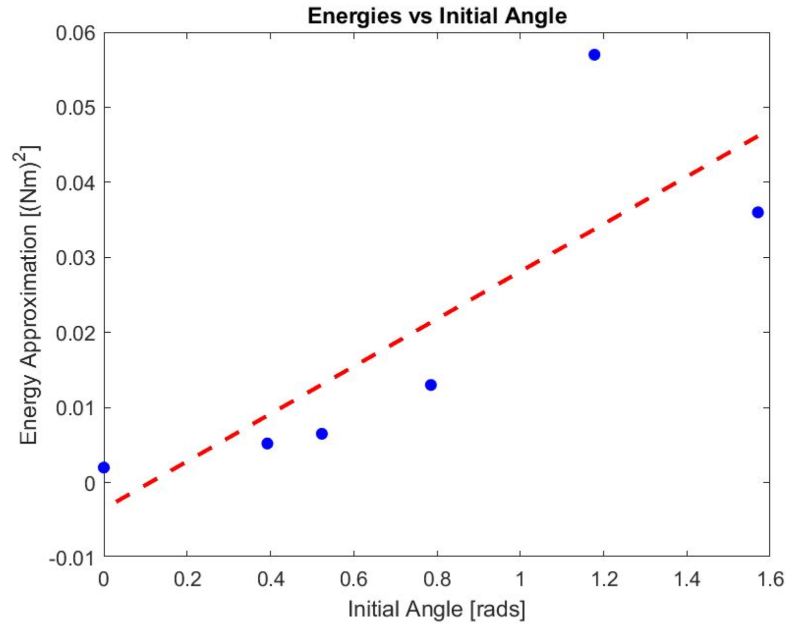
Decision Variables: 3 Bezier control points for each motor → $X = T_1,\ T_2$

Constraints:
Torque limits of the motor → $\text{s.t.} \quad T_{min} \leq T_i \leq T_{max}$
Pancake must land on the pan → $r_{pan_A} \leq r_{pc} \leq r_{pan_B} \quad t = t_f$
Pancake must flip by 180 degrees → $\theta_{pc} = \pi \quad t = t_f$

Simulation Results

We optimized trajectories for energy of multiple initial configurations.

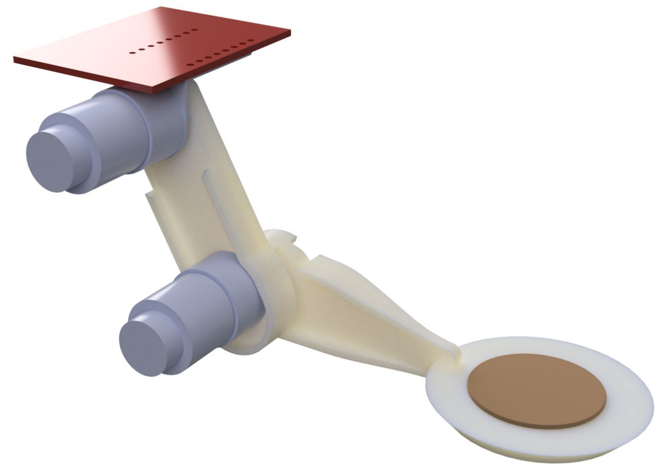




We found there is some positive correlation between arm extension and how much energy is required for flipping the 2D object.

Starting configurations with a more retracted arm correlated to more energy efficient pan-flipping trajectories for our simulation.

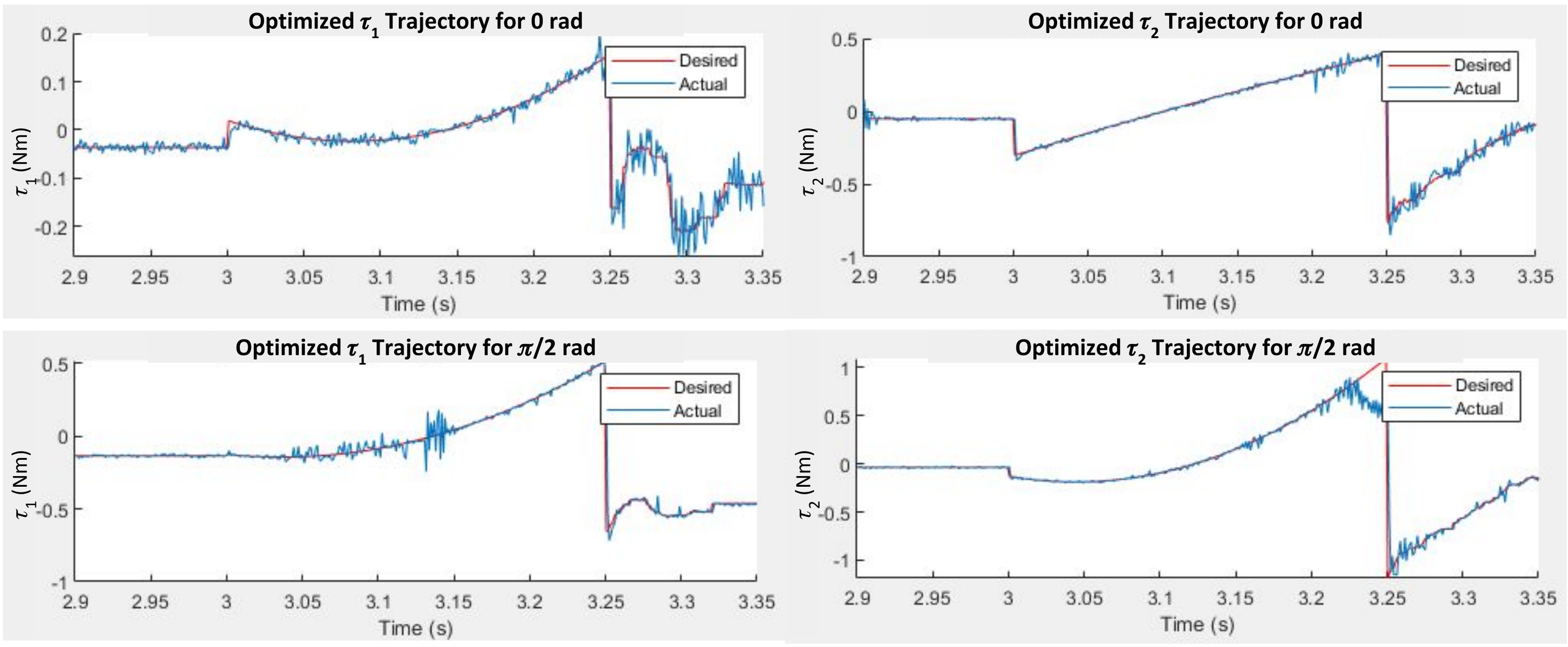
Experimental Methods



Robot Design: To follow the same 2 DoF system from simulation, two links were 3D printed with the pan being part of the elbow link. The pancake was represented by a circular and light cardboard disk. The shoulder motor has a 30:1 gear ratio while the elbow motor has a 19:1 ratio. The larger ratio for the top motor is to ensure that enough torque can be generated to lift the lower arm and motor.

Control Strategy: The hardware control was based off the optimized torques found during simulation. These were "replayed" and tracked for multiple starting configurations in the hardware.
After flipping the pancake with the optimized torques, the arm tracked a fixed position using a joint PD controller to catch the pancake. This position does not adjust to the pancake landing location but is a fixed approximation of where the pancake is expected to land.

Experimental Results



2 of the torque trajectories (0 rad and $\pi/2$ rad) from 6 initial angles tested ($0, \pi/8, \pi/6, \pi/4, 3\pi/8, \pi/2$)

All 6 torque trajectories (2 plotted above) followed a similar pattern. Initially (at a time of 3s), the board commanded a torque around 0 Nm, decreasing slowly to a slightly negative torque. As the trajectory time increased, both torque commands also increase to provide that upward impulse to the pancake.

Discussion

As one can see from a subset of the graphs plotted above, we found that all 6 locally-optimized torque trajectories in simulation followed a similar pattern to our guesses based on human intuition in the hardware. Around half of optimized trajectories in simulation led to a successful flip in hardware, showing promise of the simulated objective despite a very short trajectory period.

In the optimization, we found that flipping a pancake had many local minima due to the high dimensionality of the problem and cost function. We therefore had no guarantee the solutions or energies found were the global minima.

Conclusion

At configurations where the arm was more extended, we found there was a higher energetic cost most likely because of the jacobian of the pan being maximized for speed in the vertical direction, but not able to apply a large force to toss the pancake

Flipping and catching an object is a complex task which requires a lot of precision, and its most sensitive to the torques produced by the link closest to the object.

References

[1] Catto, Erin. (2005). Iterative dynamics with temporal coherence. Game Developer Conference.