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Fault Recognition and Mitigation in Food Processing Equipment

Dr. David R Mikesell P.E., Ohio Northern University

David Mikesell is the Ella A. and Ernest H. Fisher Professor of Mechanical Engineering at Ohio Northern University. He joined the faculty after graduate work in automotive engineering at Ohio State, six years designing automated assembly machines and metal-cutting tools, and service as an officer in the U.S. Navy. His research interests are in land vehicle dynamics, autonomous vehicles, manufacturing, and robotics. Since 2015 he has served in leadership of the ASEE Mechanical Engineering Division including roles as Division Chair and Program Chair.

Nathan Maenle, Ohio Northern University

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Nathan Maenle and David Mikesell
Department of Mechanical Engineering
Ohio Northern University
Ada, Ohio 45810
Email: n-maenle@onu.edu, d-mikesell@onu.edu

Introduction

Several years ago, the owner of a local fast-food chain approached faculty at Ohio Northern University (ONU) with a project proposal. His restaurant has prided itself for decades for custom forming its hamburger patties out of fresh ground beef, as many as 3000 patties per day in each store. The commercial equipment used for this was designed in the 1950s[1,2] and was produced through the 1970s. Since that time, the equipment has been out of production and even spare parts have become very hard to find. As his patty-maker equipment aged, the owner investigated modern alternatives, but he was dissatisfied with the quality of the patties produced. He asked if a team from the university could produce a machine which could form patties with the same consistency as the old, but without the reliability headaches of the old and the difficulty in procuring repair parts.

This project was assigned to a group of four senior mechanical engineering students as the focus of their capstone project. The process ultimately produced by this team employed the original machine components to form, cut, and stack the patties, thus preserving the identical patty characteristics. The motion and control of the process, however, was entirely modernized. This successful design was tested and proven, then replicated, and now these machines make thousands of patties each day in each of the chain's three stores.

Though the owner has been quite pleased with the new machine, he expressed interest in adding some features to help his staff anticipate when key components were degrading and would soon need replaced. This will ideally enable him to replace these components at a convenient time before they cause problems for the staff. An ONU undergraduate student was given the scope of this work as an "honors project" for his Honors program. This work was performed as an extension of an Industrial Controllers technical elective course taken in Fall 2023. This laboratory course covers applications in control systems concentrating on Programmable Logic Controllers (PLCs) and Human Machine Interfaces (HMIs). Several features were added to the machine and its controller to identify component degradation and give the operator a clear indication of the fault. Another feature was added to resolve a different common fault in the patty-maker machine. Before examining the new features, it will be helpful to present an overview of the original machine and its capstone upgrade.

Background: Original machine upgrade

The original equipment may never have been designed for the type of high-volume use which it experienced in these restaurants. Designed in the era before electronic controls, both the patty maker (Figure 1) and stacking machine (Figure 2) were controlled by mechanical limit switches, cams, and solenoids. The trigger/release mechanism of the patty machine, on the right in Figure 1, controlled AC current to the solenoid (#42) which pulls down the knife blade. The compound-action cam in this trigger/release mechanism had no features on the eccentric shaft (#64 in the diagram) for positively locating the trigger finger (#44). Correct function of the machine required repeated guess-and-check tightening of the trigger's tiny set screw; any slight variation or slipping of this adjustment caused a malfunction.

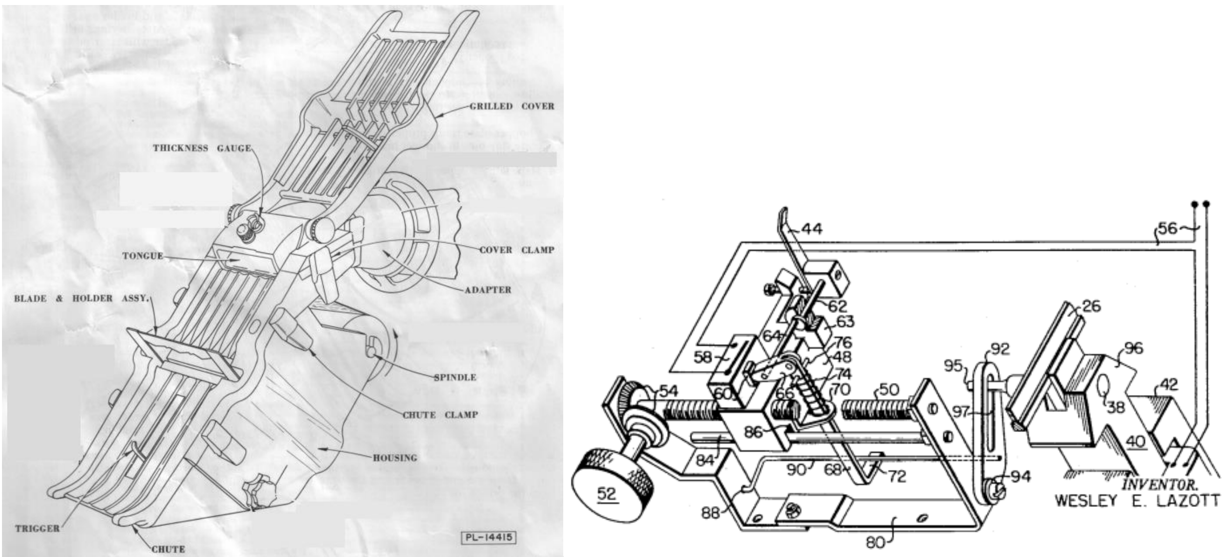

Figure 1: Original Hobart patty machine assembly[3] (left) and trigger/release mechanism[1] (right)

On the patty stacking machine (Figure 2), the cams driving the lift plate (#59-63) and the jaws (#41, 44) were made of cast aluminum. These soft cams quickly developed grooves which affected the machine action. The cams were also not trivial for local machine shops to replicate when the wear became excessive. Both the patty machine and stacker were driven by clever mechanisms, but they were insufficiently robust for the needs of these restaurants.

The redesigned machine is shown in Figure 3. The components touching the hamburger, all the way through the process, are unchanged. The hamburger is continuously extruded into a rectangular cross-section after exiting the grinder, and the patty maker cuts the patties to length. After they are cut, the paper-backed patties slide down the chute onto the stacker where they are stacked from the bottom up.

The slicing action on the patty maker still involves a solenoid-actuated knife. The action of the knife, however, is no longer controlled by the mechanism shown in Figure 1. The new controls can be seen in the right image in Figure 3. (For clarity, the form and knife have been removed to show the sensors.) The trigger finger (#44) closes the limit switch (#56), which sends a signal to the PLC to fire the knife solenoid. A proximity switch detects when the knife reaches the bottom of its stroke, allowing the PLC to open the solenoid relay and allow the spring-loaded knife to pop back up.

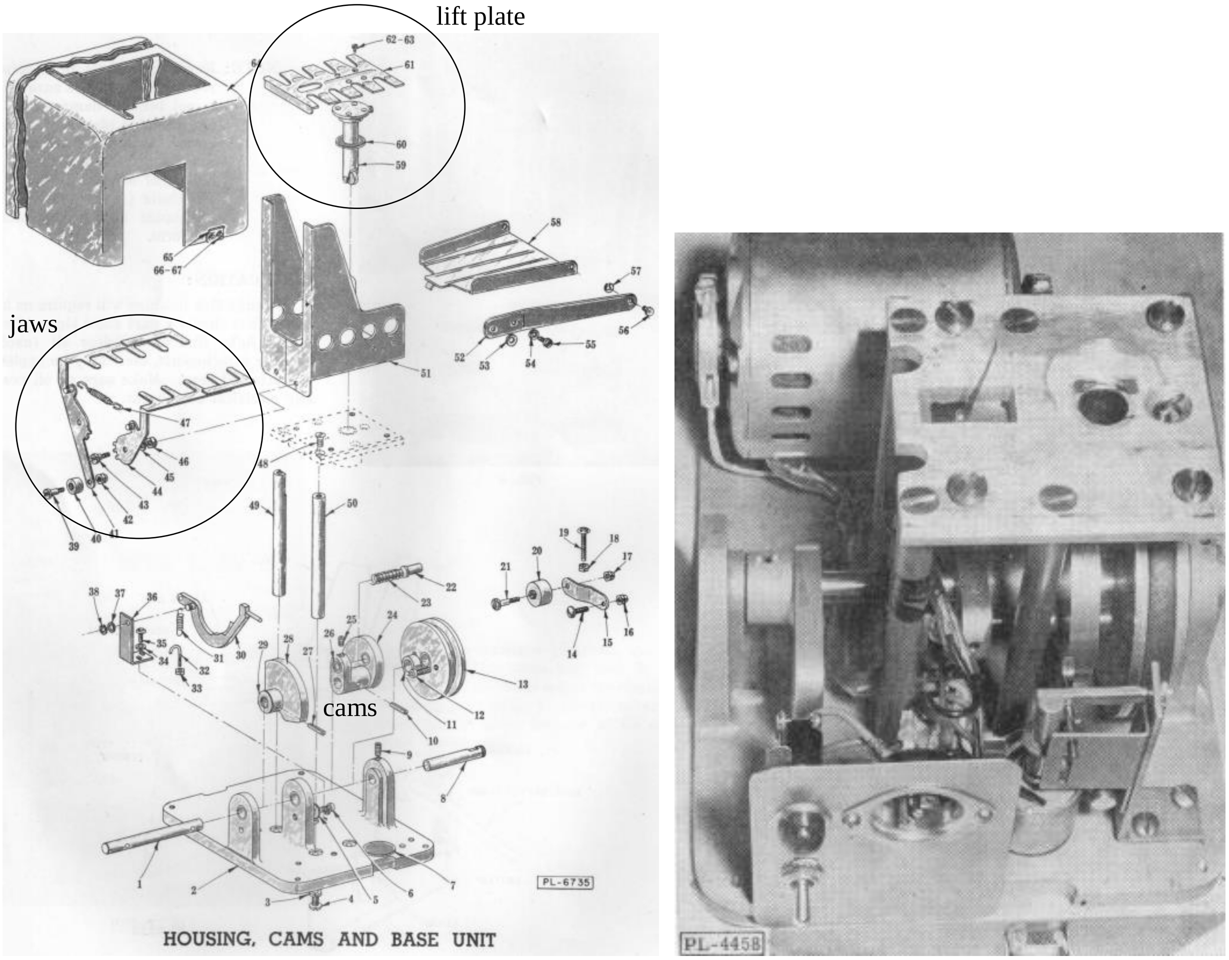

Figure 2: Original Hobart patty stacking machine. [4]

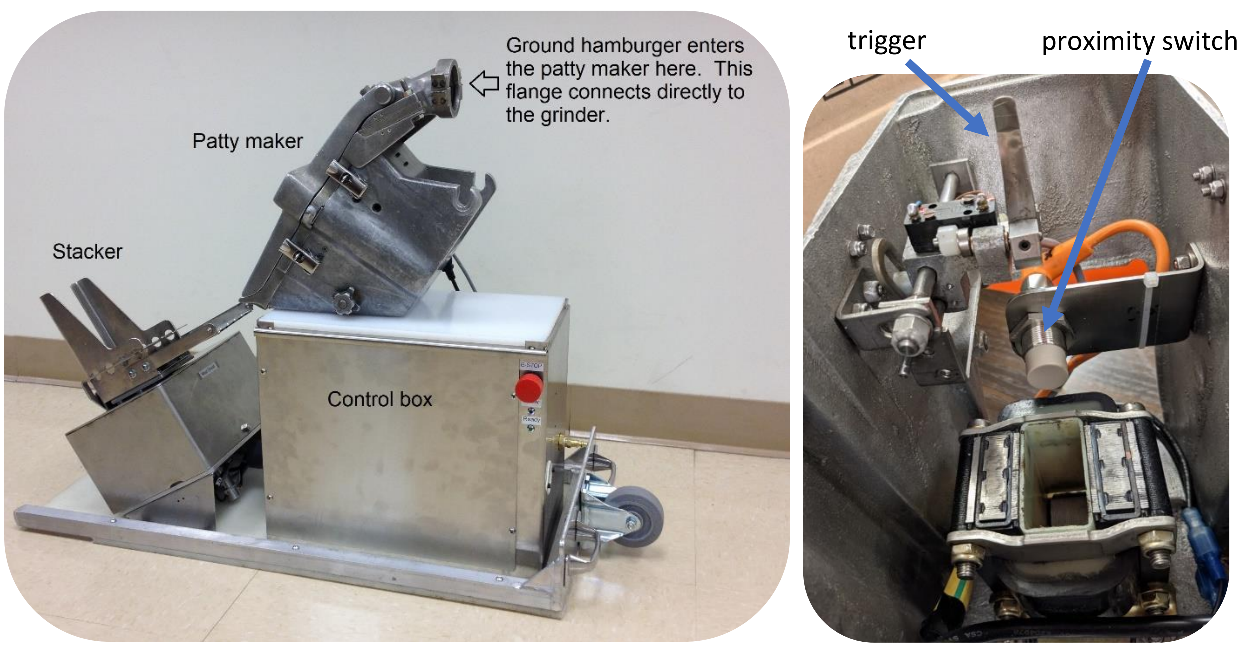

Figure 3: New patty maker hardware. Full assembly (left) and patty maker internals (right).

The speed of the slicing and stacking operations is critical. The speed of the process is driven by the rate at which the hamburger is extruded from the grinder, which is neither regular nor predictable, neither is it controllable by this machine. At its fastest, this machine must slice and stack four or more patties per second.

On the stacker, the complex cam- and solenoid-driven mechanism has been replaced with two single-acting air cylinders (one shown in Figure 4, right). The presence of a new patty in the stacker is still detected with a trigger and limit switch, but the position of the lift plate and jaws are sensed by electronic sensors attached to the cylinders. These sensors detect the magnetic field of the permanent magnet on each cylinder's piston. Coordination of the stacker motion is also handled by the PLC in the control box.

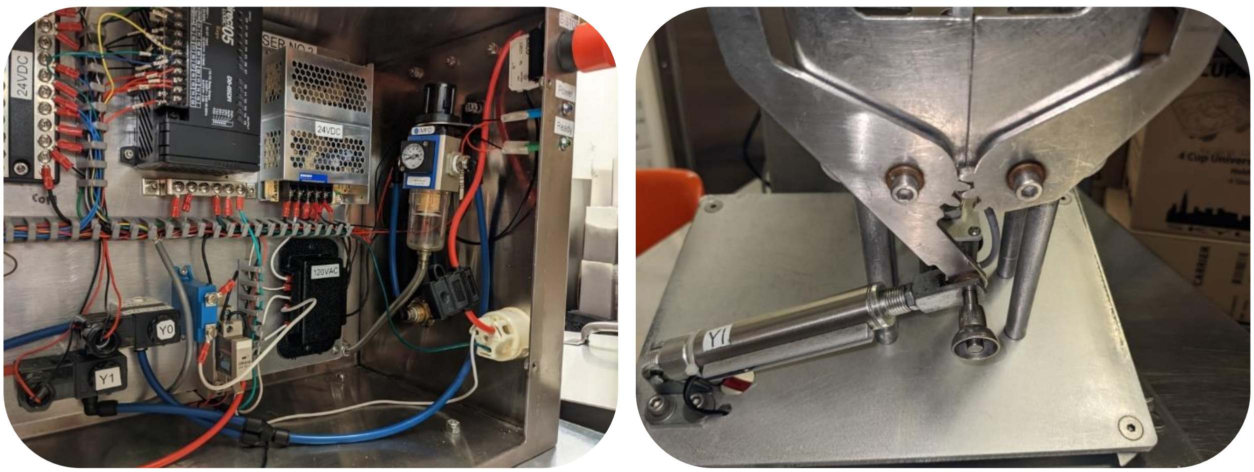

Figure 4: Control box (left) and stacker mechanism (right)

New machine update: Alerting to actuator degradation

The three main actuators on this machine are the knife solenoid and the two air cylinders. As described before, the owner requested some ability to identify when these key components were degrading and would soon need replaced. The owner was most interested in this ability because of the relative complexity of these part-replacement operations relative to other common failures (e.g. relay replacement). Of these three actuators, the most awkward to replace is the solenoid, secured by screws to the bottom of the patty maker, underneath other components. It was decided to begin with this actuator.

The mechanism of failure for the AC solenoid is most often heat-related degradation over time within the coil. The solenoids in the current apparatus last significantly longer than in the original machine, but they do not last forever. Sometimes the failure appears suddenly; more often a gradual deterioration is observed by the operators.

When the insulation between the coil windings deteriorates, the magnetic field within the solenoid does not instantly dissipate when the circuit is opened. This causes the knife to stay down longer than desired, resulting in a jam when the hamburger piles up against the side of the blade. When the delay grows excessive, the machine clogs and the operator must stop and clean it out.

Several diagnostic solutions were contemplated. One was a separate test bench where the actuators could be evaluated outside of the normal machine operation. Another potential solution was to install a separate diagnostic PLC program on the machine, coupled with an HMI (human-machine interface) touchscreen to initiate various tests and display the results. The third option was to integrate diagnostic measurements into the standard operating PLC program and employ the unused PLC outputs to indicate when a problem was sensed.

The decision was made to implement the last of those options, to integrate the diagnostics into the operating program of each PLC. Though this would somewhat limit the information available to the operator, it is the least expensive of the proposed solutions, and it enables the rapid real-time evaluation of any of the chain's six machines without requiring the presence of or connection to separate diagnostic hardware.

For the solenoid, then, a timer was added within the PLC program to measure the delay between the opening of the solenoid circuit and the time that the "knife down" proximity switch is lost, meaning that the knife has begun its spring-loaded travel back to its normal position. Measurements from a healthy patty maker revealed that this "bottom dwell" period averaged 30ms. With a degraded solenoid, this time delay can exceed one second.

The only remedy is replacing the solenoid. But if the degradation can be observed before it causes operational problems, then the solenoid can be replaced at a convenient time. To make this happen, a modification was made in the PLC program. The program now stores the most recent six sequential values of the bottom dwell timer and computes the average of these six values. If this average exceeds 50ms, PLC output Y5 is enabled and its associated LED flashes slowly on/off. If the average exceeds 70ms, the LED flashes quickly.

A similar diagnostic update is contemplated for the single-acting air cylinders on the stacking machine. The failure mode typical for these cylinders is the gradual weakening of the spring for the return stroke, which slows the closing of the jaws or the lowering of the stacker lift plate. Currently a fish scale is used to manually test the strength of this spring against the spring strength in a new cylinder. Most often, however, this is only done as a troubleshooting step when the stacker operation has already become problematic.

When either facet of the stacker operation becomes too slow, it is unable to keep up with the pace of the patty maker and cannot properly stack the patties. A benchmark spring-return time will be established for each of the two cylinders, and a separate flashing LED can be turned on when the cylinder operation begins to slow.

New machine update: Eliminating double firing of the knife

To understand the need for the next update, a description of the safety circuit is required. The patty maker "form" pictured in Figure 1 shows the hinged grill cover in its open position. This exposes the solenoid-powered knife, which for safety reasons must never fire when the cover is open. A switch flag attached to this cover trips a sensor when the cover is closed, enabling the solenoid to fire.

With age, the hinges on some of the forms have loosened up. When the knife solenoid fires, which is a violent operation, sometimes there is enough movement in the form that the safety switch momentarily loses the switch flag, opening the solenoid circuit. When the switch flag is again detected, if the "patty present" switch is still enabled, the knife solenoid will fire again. This action causes the creation of very short patties which must be deftly (manually) removed from the stacker before they jam the stacking operation.

One solution would be to rebuild the forms to improve the rigidity and alignment of the hinges. Ultimately this step becomes necessary when the hinge operation of a given form degrades too far. A shorter-term solution, however, can be used to make this safety circuit more robust without compromising safety.

The problem observed in this system is analogous to the issue of switch bouncing in an analog circuit. When a mechanical switch or pushbutton is engaged, two metal parts come into contact to bridge the circuit. These two parts, however, do not connect instantly; rather, they "connect and disconnect several times before the actual stable connection is made."[5] This results in multiple triggering as if the button is pressed and released multiple times. Solving the switch bouncing problem is called "debouncing," and can be implemented in hardware or software.

A software solution, coded into the PLC program, was selected for this application. The program now works as follows. The solenoid becomes safe to fire when the safety switch detects the switch flag. When the switch is lost, a 150ms timer starts, and the "safe" condition persists until the timer completes or the switch is regained. The system remains safe because it is not possible for someone to open the form lid and move any body part into the cutting area in less than 150ms.

Conclusion

There were two broad objectives of this project, as requested by a local restauranteur. One objective was to resolve a situation where the knives of some patty makers were repeatedly firing too quickly and creating irregular patties that had to be cleared out by the machine operator. Another objective was to create a means to anticipate the degradation of internal components of the machine, before they caused a problem for the operator and potentially even before the operator even recognized any slowing of the machine. Alerting the operator to the degradation can allow the replacement of a component at a convenient time and improving the overall reliability of the patty-making operation.

For an honors project associated with an Industrial Controls course, an ONU student examined the options to accomplish each objective and developed modifications to make these happen. A software-based debounce circuit was created to eliminate the double-firing problem. For the fault recognition in the solenoid, a PLC timer was employed to benchmark the operation of a healthy component, then used continuously to monitor the solenoid performance and alert the operator when the performance slows down. Work is underway to replicate this latter successful diagnostic for the two pneumatic cylinders on the stacking machine.

These new functions will be evaluated by the client for a time through everyday operation. Further experience with the new program will reveal proper values for the time delays which trigger the warning lights. Once the modification meets the client's approval, the machine documentation will be updated and the new program will be implemented on all the patty making machines in the chain.

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