Smart Automated Vent Register Using an SMA Spring Actuated Rotary Ratchet

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ABSTRACT

Increasing consumer interest and demand in smart automated home systems stem from the desire to create more energy efficient and comfortable homes. A smart automated vent register for a home HVAC system would allow a home owner to control temperature on a room-by-room basis, increasing individual’s comfort in the home. Current smart vent registers on the market are expensive and complicated, utilizing gearbox and motor systems. As an alternative to these conventional actuation methods, shape memory alloy (SMA) actuators (which act like artificial muscles in response to electrically induced thermal activation) have the benefits of being simple, lightweight, compact, and inexpensive with silent operation. The SMA spring actuated pawl and ratchet mechanism presented in this paper utilizes a SMA actuator and simple wire components translating the linear SMA motion to rotary motion to control louver rotation and thus airflow and room temperature. An iterative design process was followed using both analytical and empirical techniques to design the SMA actuation system. The feasibility of the design was determined by calculating external loads (such as fluid forces) and internal loads caused by the pawls, ratchet, and SMA spring. To analyze and understand these system forces and characterize pawl and SMA spring dimensions, SMA material curves, experimental system force curves, and dimensional constraints where used. Mechanism functionality is demonstrated by the pawl and ratchet system’s ability to consistently rotate the louvers. Thus, validating the feasibility of using this simple and inexpensive SMA actuated pawl and ratchet mechanism for an automated vent register.

1. INTRODUCTION

An emerging market for smart automated home systems stems from consumers’ desires for more energy efficient and comfortable homes. Smart automated vent registers for home HVAC systems allow home owners control over temperature on a room-by-room basis. In other words one can set a bedroom to a cooler or warmer temperature than living room or kitchen verses setting a single temperature for the whole home, and thus increasing individual’s comfort in the home. Current smart vent registers are expensive and complicated, utilizing gearbox and motor systems. As an alternative to these conventional actuation methods, shape memory alloy (SMA) actuators (which act like artificial muscles in response to electrically induced thermal activation) have the benefits of being simple, lightweight, compact, and inexpensive with silent operation. The SMA spring actuated pawl and ratchet mechanism presented in this paper utilizes a SMA
actuator and simple wire components translating the linear SMA motion to rotary motion to control louver rotation and thus airflow and room temperature.

This paper first gives a broad overview of the smart automated vent register product and then goes into detail on the workings and concept of the SMA spring actuated pawl and ratchet system. An iterative design process is presented that uses both analytical and empirical techniques. The initial steps of the process consist of theoretically calculating the external loads (such as fluid forces) and internal loads caused by the pawls, ratchet, and SMA spring. Using these results an initial design of the SMA spring and pawl and ratchet mechanism was built and validated. This validation showed much variability in the actuation system making the device unreliable. To investigate the problem, experimental force measurements of the initial design were taken and analyzed. These results were compared with SMA spring material curves and it was determined that a more robust design could be achieved by reducing the pawl stiffness and comparing it more accurately to the SMA spring characteristics. This analysis lead to a simple redesign of the pawl and ratchet components which was also validated. The validation showed an increase in consistency of the systems actuation proving a more robust design as feasible. This redesign has proven that it is viable to produce an automated smart register, actuated by a simple, inexpensive SMA spring and rotary ratchet mechanism.

2. ARCHITECTURE AND OPERATION

The smart register design consists of two main components; the control panel interface and the automated vent installed into the wall or floor. The control panel interface is mounted in the room and houses a temperature sensor and Bluetooth transmitter. The user inputs a desired room temperature using a continuous slider and a screen displays the current and desired room temperatures, as well as, the system status that warns the user of any error or if the batteries need to be replaced. The automated vent opens or closes the louvers a certain amount based on instructions sent wirelessly through Bluetooth transmitters from the control panel.
The vent consists of three insulated compartments that house the batteries, actuation design, and louvers. The 2 rechargeable C batteries are housed in a case which the user slides in and out of the battery compartment after pushing a button to remove the cover. The batteries supply power to both the SMA and internal vent circuitry components. The control panel houses a separate set of batteries for the interface and control panel circuitry. The actuation design is a ratchet and pawl mechanism consisting of a ratchet wheel, passive pawl, and active pawl actuated by a SMA spring. When heated the SMA spring moves the active pawl advancing the ratchet wheel by one tooth while the passive pawl holds the ratchet wheel in position as the SMA spring cools. This ratchet and pawl mechanism opens and closes the two louvers that control airflow through the louvers’ compartment into the room, thus controlling room temperature. The pawl and ratchet control of the louvers allows the ability to hold intermediate positions or 30 and 60 degrees between completely open and completely closed.

2.1 SMA Mechanism Operation

Figure 2 demonstrates the rotational ratcheting motion of the SMA mechanism cycle using six defined stages. The first stage is the initial and resting stage of the louver’s motion. The SMA spring is completely cooled and in its relaxed position. The active pawl is disengaged and provides tension to the SMA spring, while the passive pawl is fully engaged to maintain the angle of the louver.

The second stage starts with the actuation of the SMA spring as it is heated electrically, transforming it from the cold compliant Martensite phase to the hot, still Austenite phase. As the SMA spring contracts towards its memorized contracted state, creating a tension force that pulls the active pawl down engaging and contacting it with a ratchet’s tooth. This bends the “spring” or horizontal part of the active pawl that later provides a restoring force when the SMA cools.

In the third stage the SMA spring continues to heat and transform causing the active pawl to pull the ratchet’s tooth and rotate the ratchet wheel and the louver. Meanwhile, the passive pawl disengages and begins riding against the next tooth’s face. As the tooth face forces the passive pawl away from the ratchet wheel’s center a photo interrupter senses the passive signaling the rotation of the ratchet and louver to the smart automated register’s interface.

The fourth stage occurs when the SMA spring is fully heated, contracted and mostly in the Austenite phase. The active pawl is at its maximum rotational motion, while the passive pawl ‘clicks’ over the tooth’s hook engaging.

During the fifth stage the SMA spring begins to cool with the active pawl riding up against the next tooth due to the restoring force caused by its stiffness. The passive pawl becomes full engaged and prevents the ratchet wheel from rotating back, maintaining the “new” position of the ratchet wheel and louver.

The sixth stage is identical to the first however the ratchet has rotated by one tooth and the louver is at its new position/angle, 30 degrees from its previous position.
3. DESIGN

Using our iterative design process to better perfect the SMA pawl and ratchet mechanism, we first roughly determined the feasibility of the mechanism by theoretically calculating the external and internal system forces. These initial calculations determined the SMA spring and pawl characteristics for the initial design. After testing and validating this initial design, measurements of the internal mechanism forces where gathered and analyzed by comparing the results with the SMA spring and pawl characteristics. This analyses lead to a redesign of the initial mechanism which was then tested, validated, and again analyzed to determine if another redesign is needed.

3.1 Theoretical Calculations and Initial Design

The parameters and characteristics of the initial design were determined by theoretically calculating internal and external system forces. These initial calculations of fluid, frictional, inertial, and kinematic forces determined the initial pawl, ratchet, and SMA dimensions.

Figure 1: Operation of ratchet and pawl mechanism. This operation is shown in 6 stages that are repeated to change the angle of the louver and size of vent opening.
3.1.1 External Loads and Assumptions: Frictional forces in the system largely come from the two bronze bushings holding the axle in place, labeled as $F_A$ and $F_B$. By summing the moments and forces in the equations below we were able to estimate the force due to friction as 0.00294 N.

\[
\sum F_y = 0 = F_A + F_B - F_{axle} - F_{louver} - F_{ratchet} \quad \text{(Eq. 1)}
\]

\[
\sum M_B = 0 = F_{ratchet} \cdot x_r + (F_{axle} + F_{louver}) \cdot x_m - F_A \cdot x_a \quad \text{(Eq. 2)}
\]

Fluid forces from the duct airflow, were overestimated for robustness by assuming the fluid force only acts at a single point of the louver. By taking $v_1$ and $v_2$ as the velocities on each end of the louver the fluid force is estimated at 0.00569 N

\[
F_{Fluid} = \left(\frac{1}{2} \cdot \rho_{air} \cdot v_1^2 \cdot A - \frac{1}{2} \cdot \rho_{air} \cdot v_2^2 \cdot A \right) \cdot d \quad \text{(Eq. 3)}
\]

The inertial system of the device consists of the louver, axle, and ratchet inertias. Using the parallel axis theorem, the inertia of the system, $I_{system}$, is estimated at 4.7855E-5 kg*m$^2$. The forces were summed using Equation 4 below, where $\alpha$ is the angular acceleration of the louver, assumed to be \(\frac{\pi \cdot rad}{16 \cdot s^2}\).

\[
F_{SMA} = I_{system} \cdot \alpha + F_{friction} \cdot r_{friction} + F_{fluid} \cdot r_{fluid} \quad \text{(Eq. 4)}
\]

The SMA actuation force, $F_{SMA}$, is estimated to be very small (less than 0.1 N), therefore can be assumed the SMA spring can apply about 10 times that amount (1N). This assumption determines the forces due to fluid, friction, and moment to be insignificant compared to SMA spring actuation force, and thus are insignificant in the adjustment of the louver.

3.1.2 Ratchet mechanism Forces and Characteristics: To acutely control a room’s temperature the pawl and ratchet mechanism needs to provide incremented louver positions, thus allowing control over the amount of airflow entering the room. Our ratchet design includes 12 teeth providing 4 louver positions at fully open (horizontal), 30 degrees, 60 degrees, and fully closed (vertical). The inner and outer radius dimensions of 0.3996 in and 0.5 in respectively were determined by dimensional constraints of the housing compartment. A hook was also added to the end of the tooth, to ensure actuation occurs for the required distance. Tooth hook dimensions were minimized by comparing the strength of the material and the manufacturing constraints.
The SMA spring dimensions and characteristics were determined by the actuation force required of the SMA spring from theoretical calculations and the physical space available for the SMA spring. From the SMA spring, ratchet, and containment dimensions we were able to determine the sizing of the active and passive pawls. The radius of the active pawl was found by using bending moment Equations 5 and 6 to compare to the music wire’s yield strength, ensuring plastic deformation will not occur during actuation.

\[ \sigma = \frac{M \cdot y}{I} \quad \text{(Eq. 5)} \]
\[ I = \frac{pi}{4} \cdot r^4 \quad \text{(Eq. 6)} \]

All three music wire sizes compared had smaller bending stresses than their max yield stresses. Knowing that none would yield the smallest radius was picked for the active and passive pawls to minimize the stiffness of the pawls and thus their added system forces.

3.2 Measure and Analyze Systems Forces

Validation and testing of this initial design showed much variability in the SMA spring actuated pawl and ratchet mechanism. The SMA spring, which was made in-house, did not provide consistent actuation, leading to a hypothesis that the stiffness of the designed pawl and ratchet system did no compliment that of the SMA spring. To combat this, a test of the initial designed system was preformed to take measurements of the actuation forces needed.

3.2.1 Actuation Force Measurement Test: Using the experimental setup shown in Figure 5, a load cell attached to a dial stage was used to apply force to a string attached to the active pawl. The voltage readout from the load cell was calibrated and communicated the experimental test results shown in Figure 4.
As the results in Figure 4 show the stroke needed from the SMA spring to rotate the ratchet by one tooth is 6.35mm of displacement and about 1.06 N of force.

3.2.2 SMA Spring and System Comparison: Figure 6 shows the measured system forces compared to the SMA spring material curves. As shown theoretically in Figure 6, the SMA spring should be actuating enough to provide the stroke needed to turn the ratchet one tooth. However, as seen in our validation testing the system is variable and not reliable thus a safety factor of 2 was added to the needed stroke, increasing the robustness and consistency of the system.
3.3 Redesign

To accomplish the more robust actuation with a stroke of 12.7 mm, a comparison of pawl and spring stiffness is needed. The pawl stiffness was first selected by using the following beam equation to determine the softest possible pawl that can fit into the constraints of the space.

\[ \delta = \frac{F_1^3}{3EI} \]  
(Eq. 7)

Next the operating strain levels (Figure 7) of the SMA spring were chosen based on the force difference in the experimental results. Finally the SMA spring length is determined from these strain levels and the desired stroke using Equation 8.

\[ L = L_0(1 + \varepsilon) \]  
(Eq. 8)

Figures 7 shows the final designed SMA spring characteristics. An adjustment screw was added to easily adjust free clearance to match the designed force and deflection levels.

![Figure 7: Redesigned SMA Spring Characteristics](image)

4. VALIDATION

Figure 9 shows the redesigned prototype with the new active pawl shape. The same experiment conducted on the initial prototype was performed again on the redesigned prototype. Figure 10 displays the experimental force data compared to the SMA spring material curves. This shows a stroke of 10.9 mm was achieved on the redesigned prototype which gives a safety factor of 1.7. Though the prototype did not perform exactly as predicted the results showed great reduction in the variability of the actuation increasing the reliability of the design.
This redesign has proven that it is viable to produce an automated smart register, actuated by a simple, inexpensive SMA spring and rotary ratchet mechanism.

5. CONCLUSION

The iterative design process used, proved to be a valid technique to determine the feasibility of using an SMA spring actuation pawl and ratchet mechanism to open and close a smart automated vent register. As shown in the experimental measurements of the initial prototype actuation forces, the SMA spring and ratchet system used were able to produce enough stroke for actuation. However the lack of safety factor and robustness caused variability and inconsistency in the actuation and thus proving the initial design as invalid. The results of the experimentally measured actuation forces were compared with the SMA material curves to quantitatively determine more robust characteristics for the SMA spring and ratchet components. The validation of this simple redesign showed an increase in consistency of the systems actuation proving a more robust design as feasible. The validation of this redesigned prototype has proven the viability an automated smart register, actuated by a simple, inexpensive SMA spring and rotary ratchet mechanism.