THE DESIGN AND EXPERIMENTAL VALIDATION OF AN ULTRAFAST SMART (SMA RESETTABLE) LATCH

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ABSTRACT

Latches are an essential machine element utilized by all sectors (medical, military, industrial, etc.) and there is a growing need for active latches with automatic release and reset capabilities. Shape memory alloy (SMA), due to its high energy/power densities, is an attractive alternative actuation approach to conventional methods (electrical, hydraulic) because it is inexpensive, lightweight, compact and has a fast heating response times. This paper introduces the T-latch which is based upon a compact spoooled SMA rotary actuator. The T-latch can engage passively, maintain a structural connection in multiple degrees of freedom with zero power consumption, actively release very quickly (<20 ms) and then repeat operation with automatic reset. To provide the basis to apply this latch across sectors, operational behavioral models are summarized for the key states of engagement, retention, release and reset. To demonstrate the technology, a proof-of-concept prototype for automotive panel lock was designed, built and experimentally characterized for the basic operational states along with studies of the effects of power, seal and reset force. The results from this study indicate promising suitability of the T-latch technology for a broad range of industrial applications.

1. INTRODUCTION

The ability to latch components together is an integral part of machinery. Historically latches have been passive elements, but in modern day engineering systems there are increasing occurrences where automatic resettable latches are required such as safety latches of household appliances [1-4], naval tie down systems [6], closures in automobiles [3, 7, 8], release of aircraft panels for maintenance and deployment of space structures [5]. There are several drawbacks to utilizing conventional actuators to activate latches for reset. For example, wax motors and bimetallic strips are commonly used in appliances for their low cost, but are limited by low speed and performance degradation over time [1]. Electrical motors and solenoids utilized in automotive and aerospace applications improve on the speed, but are expensive, bulky, and still too slow in time-critical applications such as deployment and crashworthiness [9]. Aerospace and automotive industries utilize pyrotechnics for their high speeds, but require explosives that introduce high shock and are not reusable [5].

An alternative approach is Shape Memory Alloy (SMA) based latches for which industry has had some limited successes including automotive trunk locks [10], hood lift release latches [8] and other closures across the vehicle [3, 7], household appliance latches [2, 3], and space payload deployment and separation [5, 11-16]. In comparison to conventional actuators, SMA is a good actuation candidate for latches because its unparalleled energy and power densities (up to 30 MJm<sup>-3</sup> and 700 kWm<sup>-3</sup> [17]) enable simpler, lighter, and more compact devices. Only hydraulics have metrics of similar magnitude, yet SMA has fewer parts and lacks the bulky and complex infrastructure of valves, compressors, and potentially leaky working fluid [18, 19]. SMA also surpasses most smart material actuation in terms of maximum stress (near 700 MPa) and maximum strain (over 7%) [17], in addition to being environmentally robust and exceptionally ductile and rugged compared to materials such as piezoceramics and magnetostrictives. Most importantly SMA wire has become economically viable for practical, high-yield low-cost applications. The primary drawback to an SMA approach is the slow response time of the material due to thermal activation. However, most latch applications only require speed during release or engagement of the latch, not both, giving ample time to cool the SMA during one part of the latching cycle. This has been recently demonstrated in automotive linear SMA active latches for hood lifts with ultrafast release times (<3 ms) [9].

This paper introduces the T-latch technology, an ultrafast rotary latch based on a novel SMA approach. The latch is capable of engaging passively, maintaining a strong, multi-degree of freedom structural connection with zero power consumption, and releasing at ultrafast speeds (<20 ms) with automatic reset. The fundamental design of the latch and governing operational behavioral models discussed within this paper provide the background for synthesizing T-latch designs across a broad range of applications. A proof-of-concept case study is given which demonstrates the technology for an automotive panel lockdown for which a prototype was designed, built, and experimentally characterized regarding the basic functions of engagement, retention, release, and reset. The promising results from this study were an important step in evaluating the suitability of this smart latch technology for industrial applications.
2. T-LATCH DESIGN

The T-latch is a generic latching technology named for the rotating T shaped member shown with the overall latch structure, components, and terminology in Figure 1 and the key dimensions and their nomenclature defined in Figure 2. The T comprises a shaft, rectangular shoulders that slide on the ramps which guide it into the slot within the gate and provide obstruction once the gate is cleared and engagement occurs, and a terminal end that extends past the shoulders and provides additional stability to the latch when engaged. The T mates with the gate interior, which has exterior triangular ramps which provides a frictional moment that twists the T-shaft during manual engagement and aligns shoulders with the slot for insertion. These ramps add an extra level of robustness so that alignment occurs even in cases of misalignment or partial reset of the T.

A full operation cycle of the latch includes four main stages: engagement, retention, release, and reset (Figure 3). Engagement occurs when the shoulders of the T are pressed down against the ramps, causing the shaft to rotate relative to the upper plate towards the slot in the gate while loading a torsional reset spring between the T shaft and the upper plate. Rotation continues until the T aligns with the slot in the gate (\(\phi = \phi_k\) as defined in Figure 3), moves into the interior, and is snapped back into the engaged position (\(\phi = \phi^{\text{Eng}}\)) by the reset spring. Once engaged, retention occurs in five degrees of freedom due to obstruction and one degree of freedom by friction: the longitudinal obstruction of the T shoulders against the upper and lower plates, horizontal obstruction by the shaft and terminal end making contact with the gate interior, frictional resistance to axial rotation between the T shoulders and gate interior (the magnitude of friction can be controlled by a seal force from springs, rubber seals, gravity, etc.), and off-axis rotation prevented by obstruction between the shaft and walls of the slot, the terminal end and lower gate, and the shoulders and gate interior. The SMA actuator controls the T position \(\phi\) and consists of a SMA wire threaded through the shaft diameter with equal lengths extending from the center of the shaft, wrapping in opposite directions around a low-friction insulating sheath, and attaching at each end to the upper plate structure. Release occurs when the SMA wire is heated resistively, transitioning the wire from martensite to austenite phase, causing the wire to contract and rotate the shaft to an angle \(\phi = \phi^{\text{R}}\), allowing clearance between the T shoulders and the rectangular slot. Full release can be achieved at this point by means of the seal force to separate the latch from the gate. As the wire cools, reset occurs by the reset spring stretching the SMA wire and rotating the T back to the initial spring-actuator equilibrium position, \(\phi^{\text{0}}\).

3. OPERATION BEHAVIORAL MODELS

Simple first-order analytical models were derived for each of the operational states (engagement, retention, release, and reset) to aid in analysis and synthesis of the T-latch given a set of application specifications. Different loads and moments are applied to the T throughout its operation as shown in Figure 4, noting that whether the load is applied depends on the state of operation. Based on these loads and moments, the governing equations for predicting T-latch motions and stresses were derived for each state.

3.1. Engagement

For the latch to engage, a downward force \(F_{\text{app}} < 0\) is applied to the latch by pressing the T against the engagement ramps. The contact between the T and the ramps causes a moment \(M_{\text{eng}}\) which must overcome the moment from the reset spring \(M_{\text{sp}}\). The spring moment \(M_{\text{sp}}\) is assumed to be linearly dependent on deflection angle according to

\[
M_{\text{sp}} = k_{\phi} (\phi - \phi^{0})
\]

where \(k_{\phi}\) is the spring constant and \(\phi^{0}\) is the undeflected spring angle. Assuming quasi-static equilibrium and Coulomb friction for the contact between the T and ramps, the downward force \(F_{\text{app}} < 0\) is balanced by the vertical components of the normal force \(F_{N}\) and the friction force \(\mu_{f} F_{N}\) such that

\[
M_{\text{eng}} > M_{\text{sp}}
\]
\[ F_{\text{app}} = -2F_r \left( \cos \gamma_r + \mu_r \sin \gamma_r \right) \]  

(3)

where \( \mu_r \) is the coefficient of friction between the T shoulders and the ramps and \( \gamma_r \) is the angle of the engagement ramps. The horizontal components of the reaction force and the friction force cause a moment about the mandrel axis, \( M_{\text{eng}} \), such that

\[ M_{\text{eng}} = F_r d_r \left( \sin \gamma_r - \mu_r \cos \gamma_r \right), \]

(4)

where \( d_r \) is the distance between the ramps. Substituting the engagement moment (Equation 4) and a linear torsion spring moment into the engagement inequality (Equation 2), the minimum force required to engage the latch is

\[ |F_{\text{app}}| > k_y \left( \phi - \phi_0 \right) \left( \cos \gamma_r + \mu_r \sin \gamma_r \right) \frac{1}{2} d_r \left( \sin \gamma_r - \mu_r \cos \gamma_r \right) \]

(5)

where \( k_y \) is the spring rate, \( \phi \) is the gate angle, and \( \phi_0 \) is the T angle when the spring is undeflected.

### 3.2. Retention

To model the retention ability of the latch, two different cases were examined: the plane of shoulder case with a load \( F_{\text{app}} \) applied in the same plane as the T shoulders and shaft (x-y plane) at an angle \( \alpha \) as depicted in Figure 5 and the normal to shoulder case with \( F_{\text{app}} \) applied perpendicular to the shoulder plane (along the \( z \)-axis) as depicted in Figure 6. For both cases, stresses due to \( F_{\text{app}} \) and the seal force \( F_{\text{SF}} \) were formulated at critical points and combined based on the von Mises relation. For the plane of shoulder case, the critical locations of interest are point A (maximum von Mises stress due to axial stress and transverse shear stress in the shaft, \( \sigma_{\text{Ax}} \)), point B (maximum von Mises stress due to axial and bending stress in the shaft, \( \sigma_{\text{B}} \)), datum C-C (maximum transverse shear in the shoulder, \( \tau_{\text{C}} \)), and point D (maximum bending stress in the shoulder). For the normal to shoulder case, the critical locations are point E (maximum von Mises stress due to axial and transverse shear in the shaft, \( \sigma_{\text{E}} \)) and point F (maximum von Mises stress due to axial and bending stresses in the shoulder, \( \sigma_{\text{F}} \)). The complete set of stress constraints is given in

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**Figure 3. T-latch operation cycle.** The diagram illustrates the state of the wire (blue being martensite and red being austenite), the state of engagement, and the T angle \( \phi \) with respect to the gate. Note that the reset spring and upper plate are omitted from this diagram.

**Figure 4. Forces and moments that the T encounters during operation.** The loads shown in 4a (with top view shown in 4b) occur due to engagement, release, and reset operations and do not necessarily occur at the same time. The retention specifications are given with respect to the longitudinal, transverse (lateral, fore, and aft), and combined directions, which are defined in 4c.
Table 1 which are important to ensure retention feasibility and optimizing T-latch designs.

3.3. Release and Reset

For the T-latch to release, the SMA wire must be able to provide a large enough moment \( M_{SMa} \) and stroke \( \phi^{(M)} \) to rotate the T through a minimum angle of \( \phi_g \) (where \( \phi^{(M)} > \phi_g > \phi^{(M)} = 0 \)) while overcoming moments due to friction between the gate and T \( M_{f,g} \) and the reset spring \( M_{sp} \). This release criterion is represented by the inequality

\[
M_{SMa} [\phi_g, \phi^{(M)}] > M_{f,g} + M_{sp} [\phi_g] 
\]  

where \( M_{SMa} \) is functionally dependent on the T angle \( \phi \), \( \phi^{(M)} \) is the martensite phase fraction \( \phi^{(M)} = 0 \) for austenite phase. The gate/shoulder friction \( M_{f,g} \) is assumed to be governed by Coulomb friction, to act evenly over the shoulder area in contact with the gate, and to have a constant friction coefficient \( \mu_g \). Estimating the maximum moment arm to be at the center of the contact area when the latch is 90° engaged, the frictional moment is

\[
M_{f,g} = \mu_g F_{SF} \left( \ell + d_f \right) / 4. \tag{7}
\]

The SMA moment can be determined from experimental wire stress-strain characterization curves such as those given in Figure 7 for Nitinol wire (15 mil) [22]. To reduce variation in strain between cycles all wire used in this study was shaken-down by cycling it in pure tension through 400 heating/cooling cycles against a 40 N load with maximum strain constrained below 4.5% based on the procedure described by Pathak et al. [20]. Based on these stress-strain curves, the force exerted by the SMA wire on the shaft, \( F_{SMa} \), can be determined given a wire strain \( \varepsilon \) (related to angle \( \phi \), martensite phase fraction \( \phi^{(M)} \) \( \phi^{(M)} = 1 \) for martensite phase), and wire diameter \( d_{SMa} \). The moment generated about the axis with a moment arm of \( d_{wrap} \) is

\[
M_{SMa} [\phi_g, \phi^{(M)}] = \left( \varepsilon_{SMa} [\phi, \phi^{(M)}] \right) \left( \pi d_{SMa}^2 \right) d_{wrap} \tag{8}
\]

Based on the equations developed for the spring (Equation 2), gate friction (Equation 7), and SMA moments (Equation 8), the latch release criterion (Equation 6) is satisfied if

\[
F_{SMa} [\phi_g, \phi^{(M)}] = 0 > k_g (\phi_g - \phi_0) + \mu_g F_{SF} \left( \ell + d_f \right) / 4 \tag{9}
\]

The actuator stroke can be estimated for the ideal case in which

\[
\frac{F_{SF}}{d_{wrap}} \geq F_{SMa} \tag{10}
\]

Figure 5. Schematic of the T-latch with a general applied load for the plane of shoulder loading case and locations of the key stresses.

Figure 6. Free body diagram for normal to shoulder loading of the T.
no friction losses occur between the sheath and SMA wire based on the change in wire length $\delta\ell = \ell_{SMA} - \ell^{(M)} - \ell^{(A)}$ and the geometric relation between arc length, angle, and radius $s = \theta R$, which yields

$$\delta\phi = \phi^{(M)} - \phi^{(A)} = \frac{1}{d_{\text{wrap}}} \left[ \frac{F^{(M)}}{\pi d_{\text{SMA}}^2} - \frac{F^{(A)}}{\pi d_{\text{SMA}}^2} \right]$$

### 3.4. SMA Actuator Load-Displacement Cycle

The actuator moment-angle load-displacement cycle throughout the latch’s operation is depicted in Figure 8. Prior to engagement, the wire phase is martensitic and in static equilibrium with the reset spring such that the T is at the martensite angle, $\phi^{(M)}$, and the SMA moment equals the spring moment ($M_{SMA} = M_s = 0$). Engaging the latch, SMA wire tension is temporarily relaxed as the T rotates and the wire goes slack, until the T passes through the slot (angle $\phi_s$) and the reset spring returns the T to the martensite angle, $\phi^{(M)}$, with the actuator and spring moments equal again ($M_{SMA} = M_s = 0$). Heating the wire causes the SMA moment, $M_{SMA}$, to increase with no T motion occurring until friction is overcome, at which point motion occurs as the moment and angle climb along the $M_{\phi} + M_p$ load line. When the T rotates the shoulders beyond contact with the gate, the SMA moment drops suddenly to the $M_p$ load line and then comes to a new equilibrium the austenite angle $\phi^{(A)}$ with a SMA moment equal to the spring moment ($M_{SMA} = M_s = 1$). The moment-angle pathway between release ($\phi_s$) and austenite equilibrium ($\phi^{(A)}$) is represented as a region in the figure since it is complicated by dynamics, partial phase transformation in quick releases, and the stress dependency on phase fraction of the SMA. The cycle completes as the wire is allowed to cool, returning to the initial position along the $M_{\phi}$ load line.

### 4. AUTOMOTIVE PANEL LOCKDOWN CASE STUDY

As a proof-of-concept demonstration of the T-latch technology, panel lockdown in automotive applications was chosen noting controllable lockdown of closures such the doors and trunk is useful for example for theft deterrence, and controllable torsional stiffness. For this study, a proof-of-concept latch was designed, built, and tested based on typical industrial specifications and assuming minimal lockdown (or four latches, one at each corner).

### 4.1. Specifications

For this case study, the specifications shown in Table 2 were adapted from Federal Motor Vehicle Safety Standard 206 [21] which specifies ultimate failure in the longitudinal direction at 11 kN and in the transverse direction (fore, aft, and lateral) at 9 kN. Assuming the four latches equally share the load, the ultimate failure specification for an individual latch is 2.75 kN in the longitudinal direction (Scenario 3) and 2.25 kN in the transverse direction. The test conditions, Scenarios 1 and 2, were defined as half the ultimate failure load. To account for the possibility of multi-directional loading, the transverse specification was tightened by defining Scenario 4 (combined) as the vector addition of the ultimate transverse and longitudinal failure criteria. Automotive latches are required to engage by applying a closure force against the latch with a force magnitude that can reasonably be applied by the user (~20 kgf). Fast response times are also a desirable feature, ranging anywhere from 3 ms to 100 ms. For this case study, a release time of 30-50 ms was targeted. It is important that the active latch doesn’t require consistent power to remain engaged and after release that the latch automatically resets for repeated use.

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Table 1. Governing stress constraints on the T-latch.

<table>
<thead>
<tr>
<th>Normal to shoulder loading model</th>
<th>Stress Constraint</th>
<th>Eq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combine axial/transverse shear in shaft</td>
<td>$S_y &gt; \sigma_g = \left( \frac{F_{SF}}{\pi d^2} \right)^2 + 3 \left( \frac{16 F_{app}}{3 \pi d^2} \right)^2$</td>
<td>1</td>
</tr>
<tr>
<td>Combined axial/bending in shaft</td>
<td>$S_y &gt; \sigma_g = \frac{32 F_{app} (h_s + t_f)}{d^3} + \frac{F_{SF}}{\pi d^2}$</td>
<td>2</td>
</tr>
</tbody>
</table>

| Plane of shoulder loading model | Combined axial/transverse shear in shaft | $S_y > \sigma_g = \left( \frac{F_{app} \cos \alpha + F_{SF} \cos \phi_g}{\pi d^2} \right)^2 + 3 \left( \frac{16 F_{app} \sin \alpha}{3 \pi d^2} \right)^2$ | 3 |
|---------------------------------| Combined axial/bending in shaft | $S_y > \sigma_g = \frac{F_{app} \cos \alpha + F_{SF} \cos \phi_g}{\pi d^2} + \frac{32 F_{app} \sin \alpha (h_s - t_f)}{d^3}$ | 4 |
| Transverse shear stress in the shoulder | $\frac{S_y}{2} > \tau_c = \frac{3 \left( F_{SF} + F_{app} \cos \alpha \right)}{4 \alpha d_t}$ | 5 |
| Bending stress in the shoulder | $S_y > \sigma_g = \frac{3}{4} \left( F_{app} \cos \alpha + F_{SF} \right) \left( \frac{L - 1}{d^2} \right)$ | 6 |
4.2. Proof-of-Concept Prototype

Utilizing these specifications, a proof-of-concept prototype was designed and built based upon the behavior models presented in Section 3. The T-latch prototype (Figure 9) developed had three main sub-systems – the T structure, SMA actuator system, and the gate (which is composed of an exterior portion responsible for engagement and an interior pocket that mates with the T). In addition to the main subsystems, the prototype had additional measurement equipment used for experimentally characterizing the operation cycle.

4.2.1. T structure

Retention specifications relating to the latch strength drove the T design, primarily the combined loading scenario (Scenario 4) for this particular case study. The key latch dimensions were selected (Figure 2) to meet the stress constraints summarized in Table 3 with an assumed design safety factor of 2 and using commonly available stock dimensions when possible. A high temperature, low-wear fluoropolymer material was chosen for the sheath because it has a very low coefficient of friction, is an excellent electrical insulator, and better wear resistance and operating temperatures than other materials in its class.

4.2.2. SMA Actuation System

The motion of the T during release and reset is governed by an antagonistic SMA wire and reset spring. The actuator design incorporates Nitinol SMA wire [22] based on its reliable known performance (Figure 8), large recoverable strains, and low cost. Constraints on release time called for the minimal wire diameter (15 mil) that is capable of the range of loads necessary for this application that can provide large strokes without overstraining the wire, chosen to be about 13N for martensite (110 MPa stress, 4.5% strain), 18 N for austenite (160 MPa, 0.4% strain), and a tension spike limited to 60N (530 MPa) during the release operation. Using the design requirement for release in Equation 9, estimating the gate friction coefficient \( \mu_g \approx 0.25 \), and substituting in the known T dimensions (Table 3) and SMA tensions, the wrap diameter was chosen to be 12.7 mm (1/4”). Because of frictional losses in the spooling packaging, the length of the SMA wire was estimated based on the equation for actuator stroke (Equation 10), tested experimentally for range of motion, and increased incrementally until 30° of actuator motion was achieved, resulting in a total SMA length of \( \sim 30 \) cm.

To select a reset spring, considering the moments on the shaft at the austenite and martensite equilibrium positions, the variation in SMA moment was set equal to the variation in spring moment according to the equation

\[
M_{SMA} [\phi^{(M)}, \xi^{(M)} = 1] = M_{spr} [\phi^{(M)}, \xi^{(M)} = 1].
\]

Substituting the equations for the spring moment (Equation 2) and SMA moment (Equation 8), the spring constant is solved to be

\[
k_s = \frac{F_{SMA} [\phi^{(M)}, \xi^{(M)} = 0] - F_{SMA} [\phi^{(M)}, \xi^{(M)} = 1]}{\phi^{(M)} - \phi^{(A)}} d_{spr}.\]

Targeting a 30° range of motion \( \phi^{(A)} \) to ensure reliable retention and substituting the known variables into Equation 12, a spring constant near 2.1 N-mm/deg was deemed to be appropriate.

Figure 7. Estimated stress-strain curves for austenite and martensite phases of SMA. The estimated constitutive laws are based on experiments conducted on conditioned 15 mil, Nitinol wire [22].

Figure 8. Graphical representation of moments on T-latch SMA actuator throughout operation. The pathway of relative moments and positions of the actuator throughout the latch operation is represented qualitatively. The path between the release and austenite equilibrium points is complicated by dynamics, heating, and stress dependency of phase fraction, and is thus represented as a region.
Table 2. Specifications for latch retention. The specified loads that the latch must withstand are given for four scenarios based on the magnitude of the applied force and the direction of loading as defined in Figure 3c. Loading scenarios were adapted from FMVSS 206 [21] assuming four T-latches used around a panel’s perimeter.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>( F_{app} ) (kN)</th>
<th>Direction</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>1 1.125</td>
<td>Transverse, z-axis</td>
<td>Remains engaged, no plastic yield.</td>
</tr>
<tr>
<td></td>
<td>2 1.375</td>
<td>Longitudinal, y-axis, ( \alpha = 0^\circ )</td>
<td>Remains engaged, no plastic yield.</td>
</tr>
<tr>
<td>Ultimate</td>
<td>3 2.75</td>
<td>Longitudinal, y-axis, ( \alpha = 0^\circ )</td>
<td>Remains engaged.</td>
</tr>
<tr>
<td>Failure</td>
<td>4 3.55</td>
<td>Combined, x-y plane, ( \alpha = 40^\circ )</td>
<td>Remains engaged.</td>
</tr>
</tbody>
</table>

Table 3. Summary of design choices for T-latch detailed design.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Design choice</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>Shaft diameter 9.5 mm ((3/8&quot;))</td>
</tr>
<tr>
<td>( \ell_p )</td>
<td>Shoulder width 16.75 mm</td>
</tr>
<tr>
<td>( d_{wpp} )</td>
<td>Wrap diameter 12.7 mm ((1/2&quot;))</td>
</tr>
<tr>
<td>( k_r )</td>
<td>Reset spring constant 2.7 Nmm/deg</td>
</tr>
<tr>
<td>( \gamma_r )</td>
<td>Ramp angle 45°</td>
</tr>
<tr>
<td>SMA wire</td>
<td>High temperature, low-wear fluoropolymer</td>
</tr>
<tr>
<td>Sheath material</td>
<td>Steel, ((S_y \approx 700 \text{ MPa}))</td>
</tr>
</tbody>
</table>

4.2.3. Gate Assembly

The gate assembly was designed to perform two main functions: to guide the T into the engaged position with its exterior engagement ramps and to mate with the T for retention. The engagement ramps were designed to be engaged with approximately 20 kgf of applied load. The coefficient of friction between the T and ramps \( \mu_e \) was estimated to be 0.5 assuming polished steel surfaces and a 20° gate angle \( (\phi_g) \) was assumed. Solving the engagement requirement in Equation 5, a 45° ramp angle satisfies the inequality and allows for 20 kgf engagement force. The ramps were milled into PVC blocks with 45° angles and stainless steel shims bonded to the surface of the ramps for improved hardness and friction properties. Designing for retention, the interior pocket of the gate was sized to mate with the T shoulders with free-running fits. The upper gate thickness \( (t_{g,u}) \) was selected based on standard stock dimensions.

4.2.4. Experimental Apparatus

A T-latch prototype was built with the dimensions in Table 3 along with additional hardware and components shown in Figure 9 to support experimental characterization. To simulate the motion of a closing panel, four slider rods with brass bushings were used to align the latch structure to the gate and four compression springs provide a combined 300 N of seal force when the latch is engaged. The length of the shaft was increased for the prototype (except for in retention tests) to accommodate an adjustable torsional reset spring fixture that allows for variation of the springs and preloads during experiments. A U.S. Digital rotary encoder measured the latch position, two Cooper Instruments load cells measured tension at each end of the SMA wire, a third load cell measured engagement force transmitted through an aluminum plate and aluminum rods to the latch structure, and a Microtrak laser displacement probe signals when release occurred. The wire is heated resistively with a Sorensen power supply while a Tektronics voltage probe and a Fluke current probe measured the electrical excitation of the SMA wire. Current, voltage, angle, wire tensions, and engagement state were recorded with respect to time using a Tektronics oscilloscope for release data and a Dell laptop equipped with a National Instruments data acquisition card and LabView software interface for continuously sampling release and reset data over longer time periods.

5. PROOF-OF-CONCEPT EXPERIMENTS

Utilizing the proof-of-concept T-latch prototype, the basic operation cycle of the T-latch (engagement, retention, release, and reset) was successfully demonstrated and performance issues relating to each stage of the latch operation were explored including the effect of reset spring preload on engagement, T geometry on retention, power and seal force on release speed, and reset spring pre-load on the latch’s range of motion.

5.1. Engagement

To ensure that the T-latch can passively engage with a simple human force of 20 kgf or less in addition to the 30.6 kgf \((300 \text{ N})\) seal force, engagement tests were conducted by pressing down the aluminum plate and measuring the peak force (plus the weight of the T-latch upper plate structure and engagement fixtures \((1.39 \text{ kg})\)). This was repeated over a range of preloads of the reset spring, 330 to 650 Nmm, estimated by noting its undeflected position and deflecting it between 120 to 240° in 30° increments using the evenly spaced notches in the reset spring fixture to anchor the free leg of the torsional reset spring. While the compression seal force springs were not used for these tests, successful engagement was demonstrated in the release/reset tests against up to 300 N of seal force. Engagement trials were repeated 3-8 times at each torsional reset spring pre-load, and average engagement force result is shown with respect to the preload from the reset spring in Figure 10 where data bars represent one standard deviation from the mean for the experimental data.
Throughout testing, the passive engagement operation was successful and consistent. The linear relationship between engagement force and reset spring pre-load agrees with the engagement model (Equation 5), but the data is offset and does not pass through the origin. This systematic error is likely caused due to the observed inaccurate approximation of the reset spring’s undeflected position. The ramp friction $\mu_g$ is estimated to be 0.4 by setting the slope of the linear data fit equal to the terms coefficient to $M_{sp} (=-k(\phi_f - \phi_0))$ in the engagement formula (Equation 5) and solving for $\mu_g$. Based on the engagement results, the latch was demonstrated to meet the specified engagement with a maximum reset spring force between ~460-590 Nmm. The tests demonstrated that the use of engagement ramps is a practical, repeatable, and robust method for passively engaging the T-latch.

5.2. Retention

The T is the critical structure that must withstand the specified loads, and thus the retention study focused on multi-directional loading of T specimens that represent the latch. The specimens, shown in Figure 11, were machined from high strength steel and due to shop equipment limitations had sharp corners where small fillets would have been preferable to reduce stress concentration. A variety of tests were performed on an Instron tensile testing machine, each applying crosshead displacements at 5mm/min while monitoring applied load. To confirm the yield specifications (Scenarios 1 and 2), each load was held for one minute, removed, and caliper measurements were taken to determine whether deformation occurred. To validate ultimate failure specifications (Scenarios 3 and 4), each load was increased until breakage occurred. To simulate the different scenarios, fixtures in Figure 13 were machined to simulate the longitudinal, transverse, and combined loading scenarios. The transverse and combined loading fixtures were designed to test two
specimens symmetrically and simultaneously to avoid loading with a large moment about the Instron’s axis of motion.

The latches succeeded in meeting all loading requirements. Testing for yield, loads were applied 40% higher than specified – 1.6 kN per specimen in Scenario 1 (transverse) and 1.9 kN in Scenario 2 (longitudinal) – and caused no deformation. Testing for ultimate failure in the longitudinal direction (Scenario 3), breakage occurred at 5.9 and 7.1 kN, successfully meeting the specification with an average 2.4 factor of safety. Testing for ultimate failure in the combined direction (Scenario 4), breakage occurred at 7.9 kN, successfully meeting the specification with a 2.2 factor of safety. Inspecting the failed specimens (shown in Figure 12), shear failure was observed to occur at corners that had no fillets. More load carrying capability is expected with fillets of proper radii, which would allow for even smaller latches to be made, fewer latches to be employed or a larger factor of safety to be applied.

5.3. Release/Reset

The key distinguishing feature of this latch is the ultrafast release and ability to reset. To examine these two related functions, several tests were conducted through the full latch cycle varying the seal force (150-300 N) and reset spring preloads (60-450 Nmm). Figure 14 shows the typical operation cycle, which includes engagement, retention, release (shown in more detail in Figure 15) and full reset. In this case, a full 300N seal force and approximately 180° pre-deflection on the reset spring was applied. When the latch is engaged, the latch tension momentarily drops and the T angle momentarily spikes as the T rotates into the gate, the SMA wire goes slack, and the reset spring re-tensions the wire and rotates the T to an engaged, retention state. The SMA wire was excited with 60A current-limited power at time zero causing the SMA to heat, increase in tension, and contract, which causes the T to rotate and the seal force springs to disengage the latch (27 ms in this trial). The overall 27 ms release time of the latch, Figure 15, can be divided into two regions: 1) preheat time spent heating the SMA wire to the transition temperature before any motion

![Figure 11. T-Latch retention test specimen.](image1)

Figure 11. T-Latch retention test specimen. The photograph shows a specimen used for the retention test prior to experimentation along with its key dimensions.

![Figure 12. Test specimens after retention tests.](image2)

Figure 12. Test specimens after retention tests. The specimen from the longitudinal tests (left) failed due to transverse shear in the shoulders and the combined loading test specimen (right) failed due to shear in the shoulders at the edge of the shaft.

![Figure 13. Photographs and diagrams of retention test fixtures.](image3)

Figure 13. Photographs and diagrams of retention test fixtures.
occurs (in this case 19 ms), and 2) transition time as the latch changes phase, rotates, and releases (in this case 8 ms). Throughout the release tests, the power supply spent a large portion of the time increasing the current due to its slow response time relative to the release speeds being measured. Based on the release sequence observed, the ability to decrease the pre-heat time – possibly with higher current or pre-heating the wire – has great potential to increase the latch release speed. After the T released, the current was turned off (after 33 ms for this trial) and the wire gradually cools, changes phase to martensite, and relaxes toward the initial tension. While full reset occurs after about a minute, 95% reset is reached within 40 seconds, and the latch can be re-engaged prior to that.

### 5.3.1. Effect of Power

The response time of the latch is indirectly related to the power supplied. Different techniques have potential to decrease the release time such as exciting the actuator with bursts of current with faster rise times (using capacitors, for example [9]) or pre-heating the wire to just below the transition temperature to decrease the amount of time heating once release is signaled. To determine release times for the latch, the engaged latch was heated with bursts of average power ranging from 200 – 2000 W with the fastest release time occurring in 18 ms. In each trial, 300 N of seal force and about 180° of pre-deformation on the reset spring was applied. The average power was determined based on the average current and voltage measurements with the upper limit on power bounded by the capabilities of the power supply. The release time is an indirectly proportional function of the average power (as shown in Figure 16) and requires an average 24 J to achieve release. While the power requirement seems high, the energy requirement is very low – only about 0.2% of the energy stored in a typical AA battery because of the ultrafast release times. Based on the energy required to release the latch, 800 W will cause release in the specified 30 ms and 4.8 kW will cause release in only 5 ms, faster than other conventional actuation methods.

### 5.3.2. Effect of Seal Force

Since the SMA wire must counter friction between the T and the gate, tests were conducted to demonstrate release under a range of pull-up forces from 150-300N. Tests employing a 0.5 Nmm/deg torsional reset spring and 9A current were repeated 5 times at each seal force with the average release, pre-heat, and transition times shown in Figure 17. Tests were run at the lower power so that the different time regions could be distinguished more clearly. Full release was achieved at all tested seal forces up to and including the 300 N force required by the specifications. While the overall release time
and pre-heat time increased with seal force, the transition time decreased, possibly due to a higher austenite phase fraction in the wire when static friction was overcome in the trials with higher seal forces.

5.3.3. Effect of Reset Spring

To examine reset operation, the angle of rotation during reset was compared to the pre-load torque from the reset spring (Figure 18). The data represent trials actuated from engaged and unengaged states, and indicate that the range of motion is not affected by the initial engagement state. While friction can affect the ability of the actuator to release (predicted by the release criterion, Equation 9), the martensite and austenite equilibrium depend only on the spring and SMA moment balance. The range of motion angle is observed to initially increase with wire tension and then level off. The trend agrees with intuition based on the shape of the martensite stress-strain curve (Figure 7). At low stress, portions of the wire lie on the martensite plateau and small increases in stress effect large increases in strain – and thus actuator deflection. Above the plateau, martensite is much stiffer and stress increases will have a lesser effect on actuator deflection.

6. CONCLUSION

This paper presents a novel latch system, the T-latch, that has the ability to engage passively (without actuation), maintain a structural connection in multiple degrees of freedom, release very quickly and then repeat operation with automatic reset. Operational behavior models were presented and utilized to develop a proof-of-concept prototype for automotive panel lockdown. The full-scale T-latch prototype successfully demonstrated latch operation through all operation stages: engagement, retention, release and reset. The latch released as quickly as 18 ms, which surpasses the release time target by a 12 ms margin. Since the minimum release time was limited by the response speed of the power supply, the latch could be made faster with alternative heating techniques making it applicable to applications requiring even faster release times. The average power applied was found to be indirectly proportional to the release time, and requiring minor amounts of energy on the order of 24 J (a fraction of percent of that stored in a typical AA battery). The release time was also shown to increase with seal force, while still being able to meet specification at 300N specification. Varying the reset spring pre-load affected the latch’s range of motion, and appeared to level off near 35° as the reset spring pre-load was increased. The latch successfully met retention specifications with a large enough factor of safety that the latches could be made more compactly or used as-is for added durability. Adding fillets in a production version of the latch is recommended for reducing stress concentration at the sharp corners, which are potential sites of failure. The T-latch design is unique from other active latches because it combines rotary motion with the high energy density, simplicity, and low-cost of SMA actuation improving upon the cost, speed, complexity, weight and size in comparison to conventional methods (wax motors, solenoids, pyrotechnic, etc) positioning it as an attractive alternative technology, subject to validation with regards to the specific use requirements, for industrial applications.

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REFERENCES


