A Novel, Autonomous Thermal Connector

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Abstract

A novel replacement for traditional wedgelocks used to mount PCB boards to cold plates is presented. This project began as part of a DARPA design competition to develop a field reversible thermal connector that could be repeatedly assembled and disassembled without the use of tools while providing constant thermal resistance. The team from UCLA was tasked with designing a new device to meet these constraints. The design meets the DARPA goals and significantly reduces the thermal resistance between the electrical board and the heat sink.

The device consists of opposing aluminum wedges, driven by thermally actuated Nitinol springs, which slide against one another to provide the requisite locking force to hold a board in place and decrease contact resistance between the interfaces. These smart material springs push the wedges towards the outside of the device, elevating the upper surface and locking the board in place on the cold plate. The design increases the contact area between the components and decreases the thermal resistance relative to current devices.

Experimental results have shown that the UCLA team has addressed the chief design problems posed by the REVCON program. Nitinol has been shown to be an effective material for use as a thermally actuated spring capable of repeatedly engaging and disengaging without the use of tools. The wedge locking force increases with rising temperature, enhancing its thermal performance. The UCLA design has been shown to out-perform similar sized current state of the art wedgelock designs in terms of thermal resistance. Reductions in thermal resistance of 30%-45% have been demonstrated and shown to be repeatable.

Our prototype design increases the interfacial contact area which has a dramatic impact on performance. This means that higher power density electronics can be utilized or that more real estate will be made available on current computer boards in order to maintain current performance. Further, the use of thermally actuated leaf springs removes the need for mechanical force for installation allowing for less installation time.

Keywords

Wedgelock, thermal resistance, autonomous, shape memory alloy, conduction, heat transfer, field reversible, thermal connector

Nomenclature

PCB – printed circuit board
Deployed – engaged wedgelock position, locked in PCB
Undeployed – disengaged wedgelock position, not locked in PCB
Autonomous – in this instance, means without user input
Cold plate – force convection flow chilled plate
Nitinol – brand of shape memory alloy
T_{board} – centrally positioned thermocouple on PCB

1. Introduction

The effort described in this work was based on a DARPA sponsored design competition to develop a field reversible thermal connector that can be implemented without the application of mechanical force that can either match or improve upon the heat transfer performance of COTS (commercial off the shelf) designs. As a basis to measure improved performance, the researchers used a typical Calmark [1,3] wedgelock for comparison and focused design improvements upon that design. A typical wedgelock is anchored to the edge of an electrical circuit board by screws or another bonding method and acts as the interface between an electrical circuit board and a cold plate. The wedgelock itself fits into a channel cut into a cold plate, as seen in Figure 1, where it is deployed in order to hold it in place.

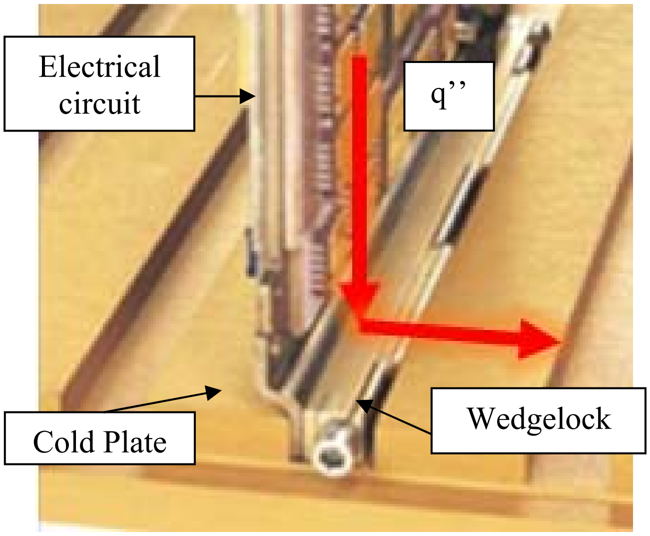

Figure 1: Schematic of implemented Calmark wedgelock

A typical wedgelock, like the one seen in Figure 1, is actuated by mechanical force on a threaded post running through the wedgelock. The screw cap, visible in Figure 1, is turned to the desired torque setting, which drives the internal locking screw of the wedgelock and causes the wedge-like pieces to expand into the cold plate channel locking the circuit board and wedgelock in place. These common wedgelocks rely on generating massive amounts of locking force in order to reduce the contact resistance between the back side of the electrical board and the cold plate channel in order to efficiently transfer heat [2]. Views of a deployed and an undeployed Calmark wedgelock, respectively, are shown in **Figure 2**.

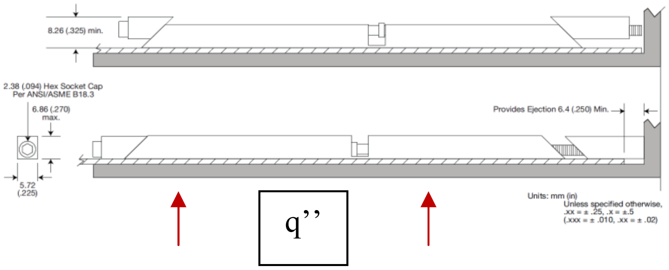

Figure 2: Calmark Wedgelock: deployed (top) and undeployed (bottom)

Note that as the wedge pieces are expanded in the vertical direction parallel to the heat flow, the contact area between them actually decreases. Thermal performance of Calmark's design is limited due to restricted surface area between its several moving parts. All of the wedge pieces in the Calmark design are hollow in order to permit the locking screw to pass through the center of them meaning that the contact area that the heat must pass through is a relatively small annular area. This creates a bottleneck of thermal energy transport since energy conducted in from the circuit board is absorbed into the wedgelock but can only be rejected by the walls of the cold plate by passing through the relatively small areas between wedge pieces. This bottleneck increases the local heat flux at the junction between the wedges, and thus the temperature, by Fourier's law. Furthermore, while the Calmark wedgelock is capable of large locking forces, which would reduce the thermal contact resistances between the wedges, cold plate, and circuit board, it reduces the contact area, thus amplifying the bottleneck problem.

Calmark states that its best wedgelocks in terms of thermal performance are those that have the most number of wedge pieces as this increases the total contact area between pieces and result in the most even locking force over the length of the device. However this increases the number of moving parts that can either wear out or break under the loads provided by the locking screw. Calmark also acknowledges that the locking force decreases over time as the locking screw is repeatedly put under strain.

The approach taken by the UCLA team, in order to improve the thermal performance of the wedgelock, was to attack what was perceived to be the largest obstacle to efficient heat transport in the device; the surface area between the pieces. Rather than stick to the traditional shape of the Calmark wedgelock, it was decided to try to simplify the design by radically changing the arrangement of interlocking wedges. By aligning the wedges lengthwise in the cold plate channel rather than in the transverse arrangement used by Calmark, it would be possible to have a continuous interface between the locking wedges which would drastically increase the surface area. It also has the added benefit of having fewer moving parts than even the simplest Calmark design.

In order to address the autonomous part of the design, the UCLA team utilized a shape memory alloy in order to actuate the wedges. The shape memory alloy allows the heat of the board to activate or deactivate the wedgelock rather than the user. This means a user can simply deactivate the board, thereby eliminating the heat load and reducing the wedgelock temperature below the activation point, in order to uninstall it rather than carry specific tools and spend time adjusting the torque of each individual wedgelock. Furthermore, shape memory alloys have very favorable strain recovery properties which resist cyclic fatigue [6].

In this paper, the current iteration of an autonomous wedgelock designed by researchers at UCLA will be presented. Its construction, assembly and implementation will be detailed. Experimental data will be presented which compares its thermal performance to that of a COTS Calmark wedgelock. Based on the results of these tests, future work will be suggested in order to improve the design for more widespread utilization.

2. Current Design

The wedgelock designed by the researchers at UCLA is referred to as the Mark 4c, or M4c, for short. The concept of the current design (patent pending) is to use a stack of triangular aluminum pieces in order to both provide locking force and heat transfer from the board to the boundaries of the cooling plate channel to which the board mounts. The "top" piece refers to the piece furthest from the board and the "bottom" piece, the triangular wedge that is attached to the board. The wedgelock itself is attached to the board by screws which anchor in the bottom triangle. An isometric view of a deployed CAD model can be found in Figure 3 and a picture of the wedgelock holding a board in its test setup can be seen in Figure 5.

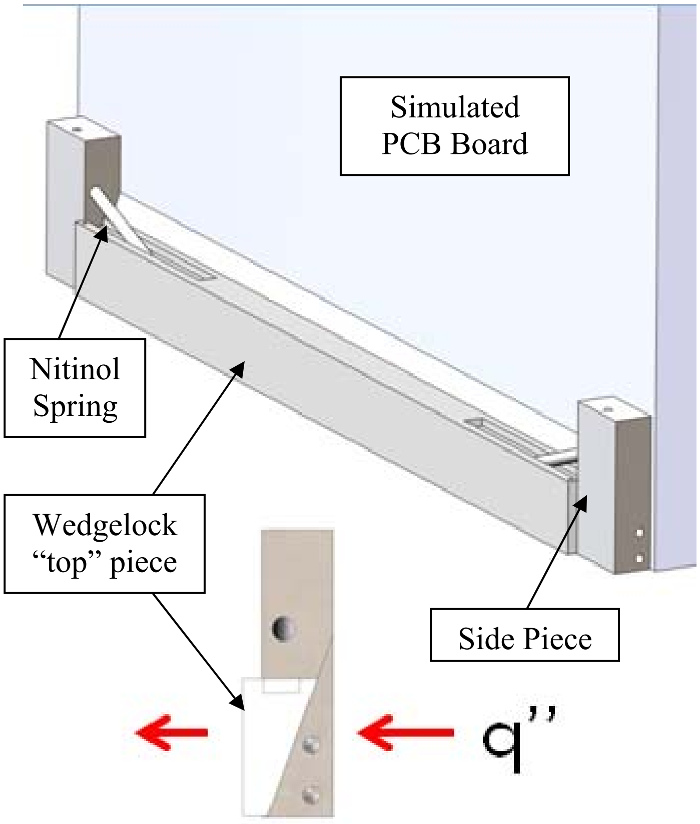

Figure 3: Prototype, deployed, isometric view

The top piece is actuated by Nitinol springs. This design greatly increases contact area because heat is transferred along the long flat surface between the interlocking triangles. A better view of this arrangement can be seen in Figure 4. In the undeployed state (meaning the actuating springs are not engaged and the wedgelock is not actively holding a board in place), the top piece is retracted. In its retracted state, the spring allows the wedgelock to be easily installed.

When the springs are activated, by reaching their transition temperature, the wedgelock is considered to be deployed and holding the board in place. The activation of the springs pushes the top piece towards the left, increasing the height of the wedgelock and locking it into place.

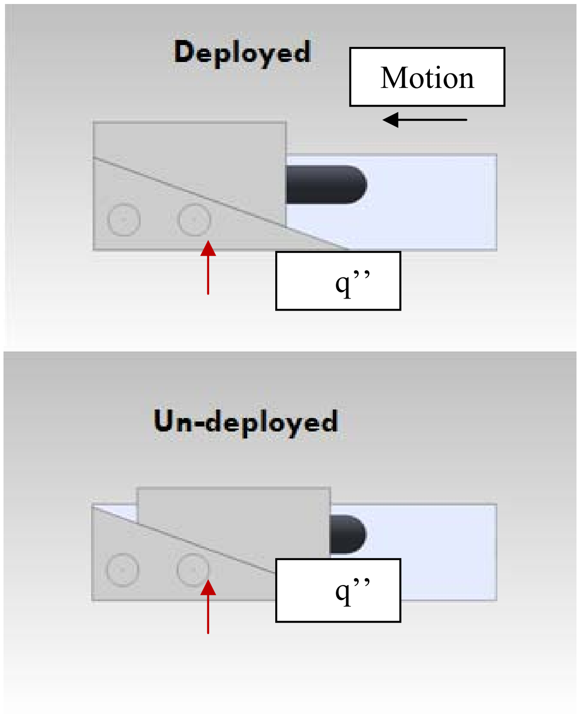

Figure 4: Schematic of Autonomous Wedgelock operation

The advantage of using Nitinol springs is that they have a change in Young's modulus as a function of temperature. A transition temperature of 30 +/- 5 deg C was selected for the M4c design, so that the device deploys above a reasonable room temperature, but not high enough to damage the board. Note that some residual force is still applied even when the spring is cold. This force is enough to hold the board in place while still being easily inserted and removed. Once activated, the spring force increases in the rod, securing the board and decreasing the thermal contact resistance. The transformation is fully reversible and the high elasticity of the alloy practically eliminates the fatigue limit that would be seen with an ordinary metal wire [5, 6].

The springs themselves are anchored in two side pieces, on either side of the stacked triangular wedges. The spring arm is angled in such a way that when the transition temperature is reached and the spring becomes rigid, the spring supplies ample force to move the top wedge into position to lock the wedgelock and board in place. The side pieces are currently held in place by screws which are anchored in the bottom triangle. These screw holes can be seen in the bottom right hand side of Figure 3.

Many considerations were made when designing the Nitinol springs and triangle wedge pieces. Some of the important parameters for the spring design include: leaf spring height, angle, length, thickness, and transition temperature. Similarly, the angle, height, and other dimensions of the interfacing triangles are also among the key parameters involved in maximizing both heat transfer and locking force while maintaining a reasonably trouble-free installation of the wedgelock.

3. Experimental Method and Results

In order to test the thermal performance of the autonomous wedgelocks, a test setup was developed to try and closely match the layout of typical operation. A channel was cut into a block of aluminum which was 0.5"x 0.5". This channel accommodated both the wedgelock and the simulated board it was attached to. The simulated board was 0.25" thick which provided only 0.25" of space for the wedgelock to fit into, forming it's widthwise design limitation. A picture of the experimental setup can be seen in Figure 5.

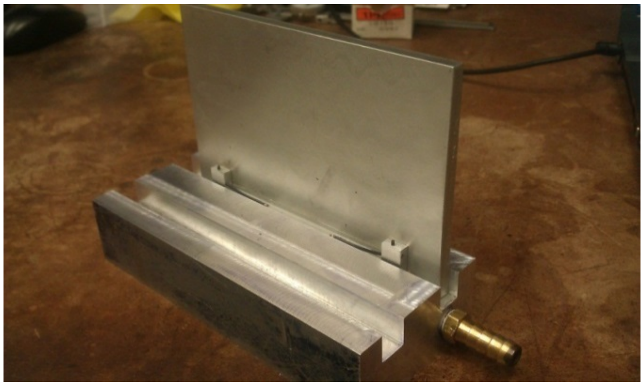

Figure 5: Experimental Test Setup

Heat was supplied to the board by a series of cartridge heaters which were attached to the middle of the simulated PCB board. The simulated board was made out of solid aluminum. The channel itself was cooled by flowing chilled water at 20 ^{o}C, through a tube cut into the test block. The hose barb for this connection can be seen in the lower right hand side of Figure 5. The entire setup was insulated in order to mitigate the effects of free convection from the surface of the board. Temperatures were measured at the center and sides of the midline of the board. Three thermocouples were placed in the junction between the wedgelock and the channel, three in the junction between the wedgelock and the board, and three more along the channel itself.

In order to operate the experiment, a particular heat flux was fixed and the thermocouple temperatures being measured were allowed to reach steady state. Steady state was determined to be when temperatures did not change by more than +/- 1 ^{o}C for 5 minutes. The steady state values of the temperatures were recorded alongside their associated heat flux and the heat flux was then increased.

The resistance of the wedgelock was calculated as the temperature difference between the simulated board and the cooling channel, in keeping with the method used by Calmark. Calmark reports its resistances as a function of length, but since the COTS design used for benchmarking was the same length as UCLA's prototype and was tested in the same setup as the new prototypes, the experimental data we obtained for both models was used for comparison, rather than reported values published by Calmark.

The cumulative resistances versus input power for the Calmark, UCLA M4c, and M4a designs are shown in Figure 6.

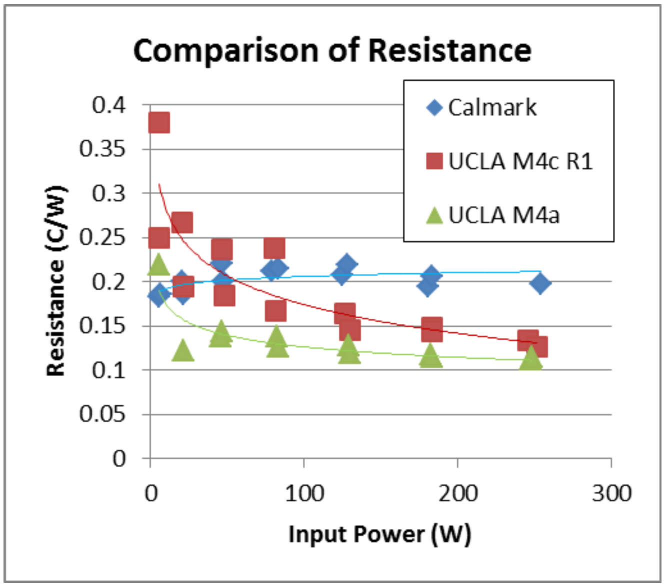

Figure 6: Comparison of Thermal Resistances

The M4a showed the best performance with a minimum resistance of 0.11 ^{o}C/W and the M4c had a minimum resistance of 0.13 ^{o}C/W. All of the experimental runs exhibited some scatter below 75W before becoming more uniform at higher input powers. The researchers believe this is due non-uniform activation of the nitinol springs. As the springs transitioned from inactivated to their activated state, their locking force can fluctuate slightly as heat is transferred through the springs. The resistance for all three designs had become mostly consistent by the time they reached 245 W.

Note that as power increased, both of the UCLA designs exhibited a logarithmic decline in resistance where the Calmark design actually increased resistance. The M4a's Nitinol spring had a lower transition temperature meaning it was activated throughout the duration of the test, relative to the M4c, which only activated above 30 deg. C. The M4a design appears to have stabilized at a constant resistance by the conclusion of the test but the M4c was still declining.

The experiment was not conducted at input power beyond 245 W because this was the limit of the heaters the researchers used. The experiment was conducted 3 times with each design to verify repeatability of the results.

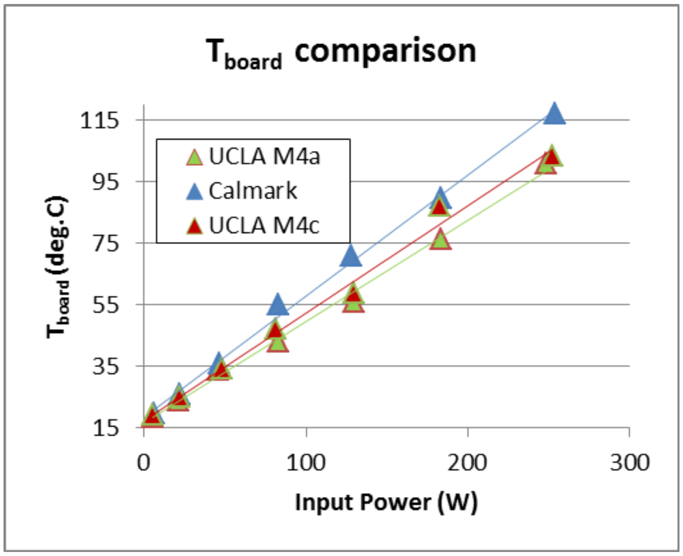

Figure 7: Board Temperature Comparison

The board temperatures were all at, or above 100 ^{o}C by the 250W power level and it was believed that higher input power would exceed the typical temperature range experienced by an actual board. Calmark's wedgelock resistance was approximately constant at 0.21 ^{o}C/W. This is half of the expected minimum value from published data from Calmark [3]. Also, as seen in Figure 7, the board temperatures of the UCLA designs are still lower than the Calmark model.

In summary, the UCLA designs reduced the thermal resistance seen with similar off the shelf wedgelock designs and also improved their performance as input power was increased. This can be shown to directly impact the temperature of the board which the wedgelock is locking in place. This was accomplished through minimizing moving parts and increasing interfacial surface area.

4. Future Work

The wedgelock presented in this work demonstrates an effective alternative wedgelock to what is currently available off the shelf, in terms of thermal resistance. For the future, it is desired to finish parameterizing all of the geometric considerations which affect thermal resistance and locking force. This characterization is ongoing and will allow the current design to be applied to many different applications.

In general, there are additional parameters that are relevant to the performance of wedgelocks which tend to be application dependant. For instance, in conditions where the environment is colder than normal, the Nitinol will require an appropriate transition temperature for the working conditions so that an acceptable transition temperature is reached when desired. Fortunately, the transition temperature for Nitinol can vary from approximately -50 ^{0}C to 160 ^{0}C [7]. Hypothetically, this would indicate that it would be possible to operate autonomous devices in these ranges but further experimental study would be needed to prove this.

Another experimental parameter that will need to be explored is vibration performance. Since the scope of the research expected by the DARPA initiative was limited, vibration testing was not prioritized but is planned for the future. However, it is worth noting that because the wedgelocks in this work are spring actuated and not screw driven, there is some natural dampening in the design that would mitigate vibration transmission to sensitive components. Further investigation could provide insights into spring designs which could further assist spring dampening in high vibration environments.

5. Conclusion

This report details the effort made by the UCLA team in order to design an autonomous thermal connector which can activate using only the waste heat provided by an electrical circuit board. The wedgelock is constructed out of opposing aluminum triangles which expand to lock the board in place and retract in order to unlock the board from its mounting. One triangle is anchored to the electrical board that it is locking in place and cooling while the other triangular piece is allowed to slide back and forth so that it can lock the board in place. Springs made out of Nitinol were used to actuate the top wedge and provide the locking force necessary to secure the aluminum plate. The Nitinol springs provide a small amount of locking force when the board is not active or "cold" and provide the prescribed maximum locking force when the board is above a chosen temperature.

Experimental results were presented which show that the UCLA design meets both stated objectives of having an autonomous design and lower thermal resistance than a COTS wedgelock. The Nitinol springs were shown to be able to self-actuate based on input power to the board. This actuation was used to repeatedly lock and unlock the board to the cold plate. The thermal resistance was shown to be constant above its activation temperature and up to 45% lower than COTS devices. The UCLA design also reduced the temperature at the center of the representative PCB board by up to 20%. These novel wedgelocks have the potential to simultaneously increase the performance envelope of current devices and reduce costs through increased energy efficiency and shortened installation/disassembly time.

Acknowledgments

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