

Ultrasonic Device to Measure Bone Cement Readiness During Polymerization

BE Senior Design

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Executive Summary

Bone cement is used to anchor artificial implants to bone or fill space in the vertebrae. It is created shortly before application by mixing monomer liquid and cement powder to initiate the process of polymerization which is characterized by four stages: mixing, waiting, application, and setting. Its timing of application is crucial in orthopedic surgeries. Our device aims to monitor bone cement polymerization using ultrasonic techniques for contactless and non-invasive methods to ensure sterility while evaluating the viscosity change. Ultrasonic waves penetrate the bone cement syringe and apply the time-of-flight and wave attenuation to measure how long it takes for the wave to travel and the loss of intensity or amplitude of that wave during the waiting and application stages. This approach aims to assist the surgical team to identify optimal window of application and improve surgical outcomes for patients.

Background

In orthopedic surgeries such as vertebroplasties or hip and knee arthroplasties, bone cement is applied to the bone to stabilize fractures or attach implants. It is made from polymethyl methacrylate (PMMA) which undergoes polymerization upon mixing of the liquid monomer and powder polymer. During this process, there are four stages which are termed mixing, waiting, application, and setting. One of the many systems for forming bone cement includes a syringe system for easy application. However, the point at which surgeons and technicians determine when the bone cement is ready to be applied is by subjective touch and feel. This assessment involves previous experience of handling bone cement. It also leaves room for error causing premature or delayed use. When it is applied too early, it can cause high pressure cement leakage leading to Bone Cement Implantation Syndrome (BCIS) but adding it too late causes poor interdigitation leading to aseptic loosening [1]. Thus, a device is proposed to measure and evaluate the readiness of bone cement for orthopedic application using ultrasonic waves with combined principles of time-of-flight and wave attenuation. With this concept, surgical outcomes for both the patient and medical team can be improved.

Experimental Setup

The completed testing plan involves having the completed 40 kHz circuitry five centimeters away from the plastic container holding PMMA powder. PMMA polymer liquid is held in a separate opaque container glass container to shield the polymer from light. Room is set to 65 degrees Fahrenheit before starting of the procedure. Fundamental testing of prototype for upgrade included evaluating the sensors at various distance.

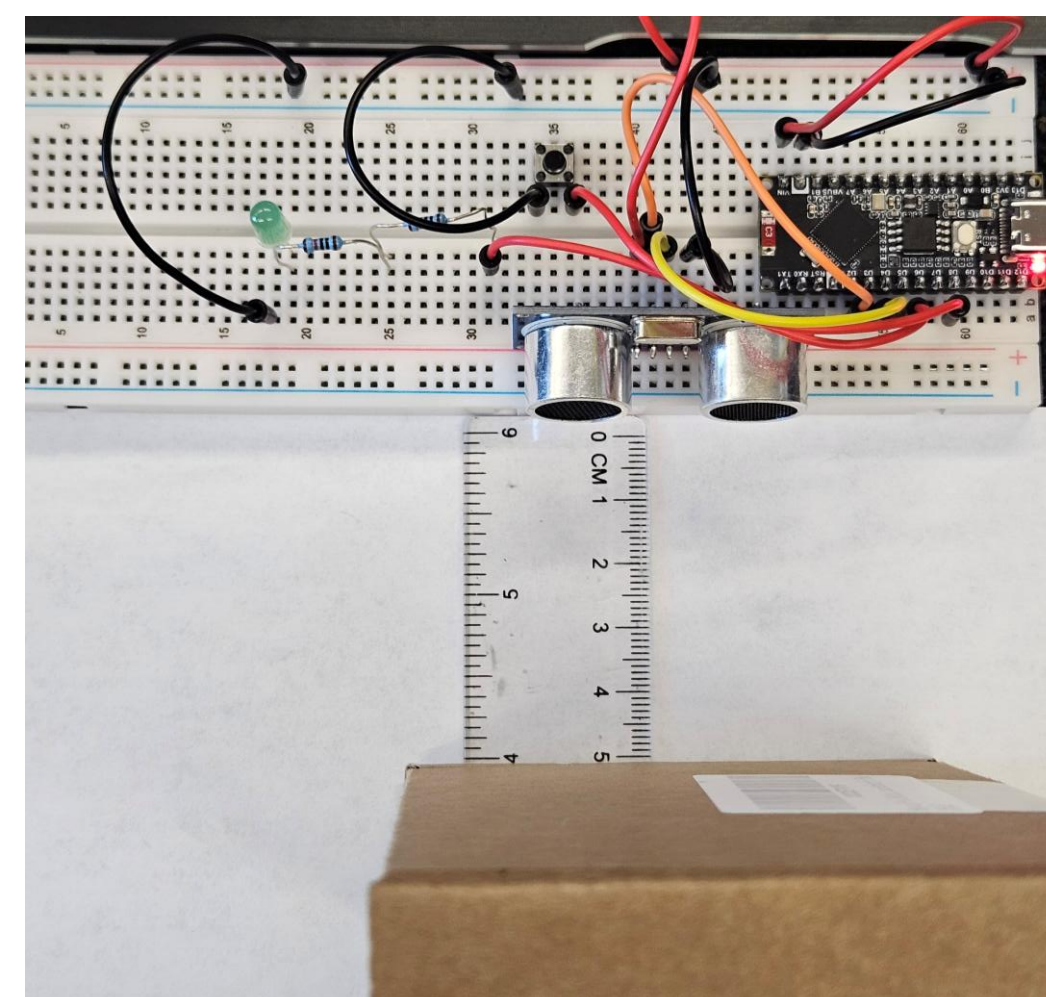


Figure 1. Preliminary testing set up of prototype.

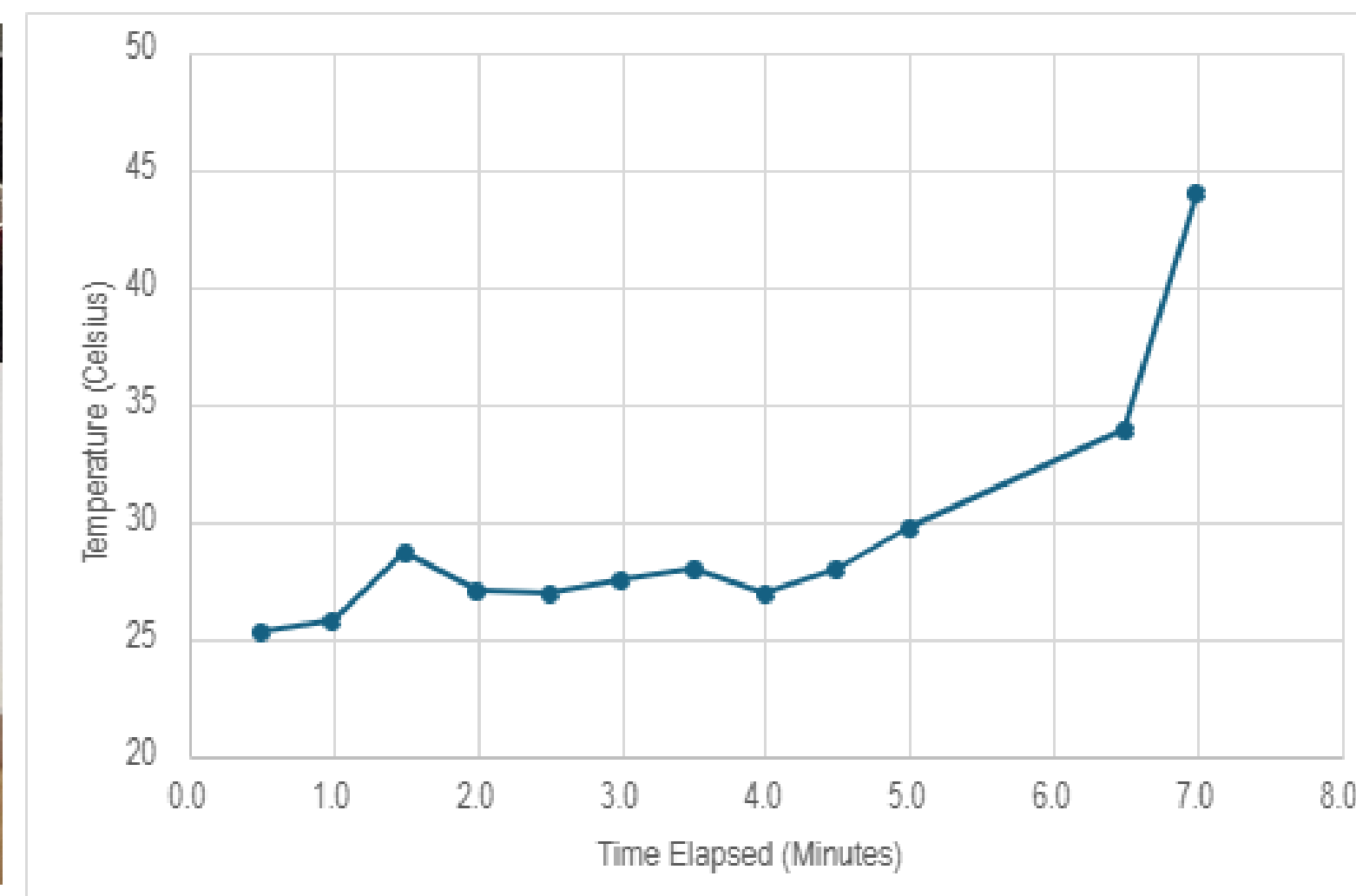


Figure 2. Initial temperature testing of polymerization..

Experimental Test Plan

Our completed testing of PMMA cement with our concurrent 40 kHz monitoring system in real-time with the Arduino Nano ESP 32 system:

1. Our instrument was placed nearby the mixing system
2. Powder of PMMA is mixed with the liquid polymer and
3. The instrument monitored the prospective system over time until completion
4. Recorded time-of-flight were recorded, reviewed and analyzed

Our updated experimental plan will entail the updated version of the 2 MHz monitoring system with clamping modification due to the change of sensor shape. In addition, wave attenuation measured will be integrated. To determine the optimal window of readiness, repeated trials will be conducted and compared with standard methods by touching the bone cement for dough texture.

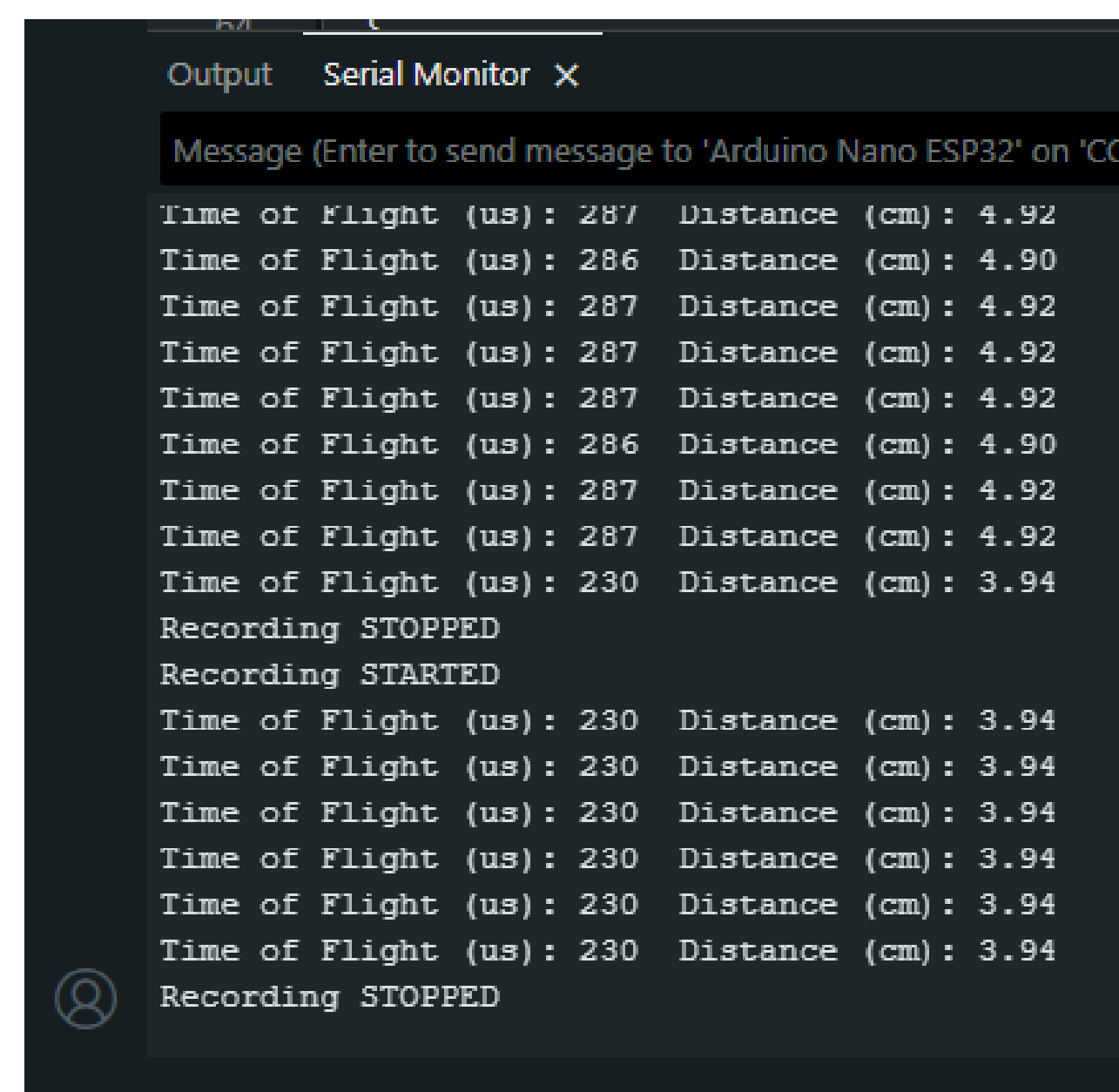


Figure 3. Data output of preliminary testing.

Experimental Results

The initial prototype serves to demonstrate the core functionality of the ultrasonic sensing system that encompasses signal transmission, reception, and data acquisition. The system was able to generate ultrasonic pulses and measure time-of-flight (ToF) responses under controlled conditions.

- Distance-based measurements using a 40-kHz ultrasonic sensor confirmed that:
 - The sensor system can reliably detect reflected signals
 - ToF measurements scale consistently with distance within a reasonable margin of error
 - The data acquisition pipeline (sensor → MCU → output) is functional
- Measurements were stable under fixed conditions; signals fluctuations were observed due to surface alignment, environmental interface, signal positioning.

The limitations of the current prototype stems from the 40-kHz sensor system operating only in an air-based distance measurement mode and therefore cannot directly measure the polymerization state but rather works as a functional baseline and not a final sensing solution of the device design.

The expected results for the final design of a dedicated ultrasonic transducer pair (Tx/Rx pair) include proper transmission through the bone cement to detect changes in material properties (increased attenuation, altered signal transmission characteristics) that correlate to the cement readiness state.

Conclusions

- This project successfully developed a working ultrasonic sensing prototype that validates the feasibility of using ultrasound for monitoring material changes. While the current system is limited to distance-based sensing, it demonstrates the core electronics, signal processing, and system integration required for the final design.
- The prototype represents a proof-of-concept system that bridges the gap between theoretical design and practical implementation and establishes a foundation for transitioning to a more advanced system that is capable of measuring ultrasonic transmission through PMMA bone cement.
- Future work includes:
 - Integration of dedicated ultrasonic transducers (Tx/Rx pair)
 - Implementation of signal amplitude and attenuation analysis
 - Development of custom PCB board for compact system integration
 - Mechanical refinement of clamp housing for improved alignment and stability
- This prototype demonstrates a scalable pathway from basic ultrasonic sensing to a clinically relevant device for real-time monitoring of PMMA bone cement curing.

References

- [1] Hunt, S., Stone, C., and Seal, S., 2011, "Timing of femoral prosthesis insertion during cemented arthroplasty: Cement curing and static mechanical strength in an in vivo model," Canadian journal of surgery. Journal canadien de chirurgie [Online]. Available: <https://pmc.ncbi.nlm.nih.gov/articles/PMC3038367/#:~:text=Theoretically%2C%20if%20the%20prosthesis%20is,and%20provide%20better%20initial%20fixation.> [Accessed: 06-Apr-2026].