RESEARCH PROPOSAL DESCRIPTION

A. PROJECT TITLE: Next Generation On-Board Sensor Technologies for Rolling Stock

B. START & END DATES: June 1, 2023 – August 31, 2024

C. PI & Co-PI(s): Heinrich Foltz (PI, UTRGV), Ping Xu (Co-PI, UTRGV), Constantine Tarawneh (Co-PI, UTRGV)

D. PROPOSAL ABSTRACT

In prior work, UTCRS has developed on-board, wireless sensor technology that makes early and accurate detections of defect initiation in railcar bearings and wheels. This technology has been transferred to industrial partners for field trials, and in the first deployment detected a condemnable wheelset. For the current project, we will develop next generation sensors to enable (a) detection of a wider range of safety hazards, including damaged couplers, track defects, and load shifts, (b) even earlier predictions of failures, and (c) further reduction of false positives. The key to these advances will be coordinated sensors with precision synchronization at the level of tens of microseconds and relative position self-awareness at the centimeter level across an entire train, combined with an order of magnitude improvement in sensitivity. This will provide richer datasets that allow comparison of signatures from different bearings on the same bogie, different bogies on the same railcar, and different railcars on the same train.

The challenge is implementing these improvements within limitations on power consumption and communication bandwidth. In this 15-month project we will design, fabricate, and demonstrate new modules that add temporal and spatial awareness to existing vibration, load, and temperature sensing. Due to power consumption and spatial accuracy requirements, this cannot be readily accomplished with GPS or other COTS systems at the wheel level; instead, a dedicated on-board system must be developed. The data acquisition will also be improved based on lessons from past projects, with the goal of obtaining a ten-fold improvement in resolution and sensitivity.

This project addresses DoT strategic goals in safety, economic strength, equity, sustainability, and transformation. The deliverables include a documented design and demonstrated prototype suitable for technology transfer and/or field testing. The system will provide a testbed for future experiments and a data stream for development of future analysis techniques.

E. DESCRIPTION OF RESEARCH PROJECT

E.1 PROBLEM STATEMENT

Derailments due to wheel, bearing, or track defects cause a significant number of chemical spills, service stoppages, and fatalities each year. Even failures that are identified prior to causing a derailment have economic impact due to routes blocked for field repairs. Systems based on wayside detection or human inspection do not provide continuous monitoring and typically only detect impending failure and fail to catch a significant number of hazards. Previous research [1-3] has indicated that wireless sensors mounted on railroad suspension components can effectively predict the need for bearing replacement tens of thousands of miles in advance and are now undergoing limited field implementation. Furthermore, a combination of multiple sensing modalities in one sensor (temperature, vibration, bearing load, and location awareness) has the potential for early detection of wheel defects, rail irregularities, and shifts of railcar load.

Previous work focused on individual, autonomous sensors spontaneously reporting detected problems through a network to a central hub. With widespread deployment on multiple bearings throughout a train, a new opportunity arises to fuse data from multiple sensors to (a) detect and identify entire new classes of hazard, and (b) improve accuracy for classes of hazard that are already detectable. Examples of the use of data from multiple sensors to improve accuracy and to isolate sources of impact is summarized in Figure 1.

This opportunity depends on having access to multiple sensors with precision synchronization of data collection (perhaps 10 microseconds or better) and accurate system awareness of sensor position (within a few centimeters). The long-term aim of our project is to build a deployment-ready system capable of making and then analyzing such measurements. For the current 15-month project, we plan to design and build the required electronics and embedded software, while laying foundations for machine-learning based analysis of the field data to be obtained in later projects.

E.2 RELEVANCE TO UTCRS THEME AND THEMATIC THRUST AREAS

The relevance of this project to the University Transportation Center for Railway Safety is clear. We are directly targeting a major safety concern in rail transportation, derailments, and specifically the thematic thrust area in rolling stock. Our ability to distinguish track impacts from sources within the train allows us to also address the thrust area in track safety.

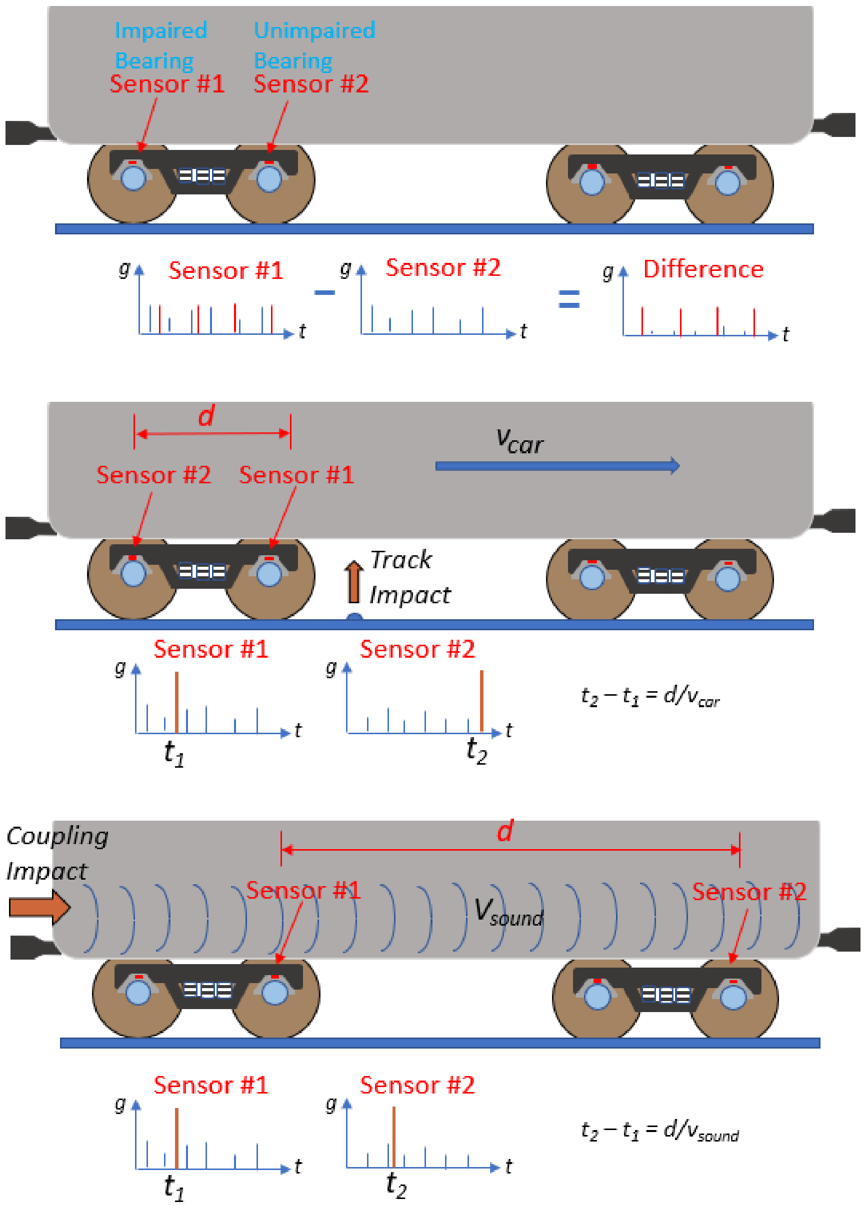

Figure 1: Exploitation of multiple synchronized sensors to improve accuracy and capability of vibration sensors. (Top) Comparison of signatures from two bearings on the same side frame can be used to partially cancel noise sources originating in other parts of the railcar. (Middle, Bottom) Sources of single impact events can be distinguished through differential timing combined with sensor position awareness.

E.3 ALIGNMENT WITH USDOT STRATEGIC GOALS

(a) Safety: The project directly addresses safety through earlier and more accurate detection of impending failures in bearings, wheels, and other railcar components. The improved system also has potential to detect track damage and railcar coupling impacts that exceed recommendations. **(b) Economic Strength:** Unscheduled stoppages and field repairs cause serious economic losses for rail companies and their customers, and other users of the track. Early prediction allows repairs to be deferred to scheduled maintenance periods that will not disrupt the rail transportation system. **(c) Equity:** UTRGV is a minority serving institution with an established record of training students from underrepresented groups and placing them in professional positions in the transportation industry. This project will directly employ two students, and indirectly support the employment of several others. **(d) Sustainability:** By enabling proactive preventive maintenance, this project will extend the useful lifetime of rolling stock, and thus amortize the carbon footprint of manufacturing a railcar over a longer period. It will reduce the number of environmentally-significant derailments. **(e) Transformation:** The extensive high resolution data streams generated by the next generation sensors will be a rich resource that can be mined for new insights beyond the currently envisioned application, using recent and future advances in machine learning.

E.4 RESEARCH APPROACH AND METHODS

This section outlines our overall approach. A detailed description is given in Section E.5.

A single car system, whether deployed in the field or in the lab, will consist of eight modules mounted on the bearing adapter (see Figure 2 in Section F). This location has the advantage of close mechanical and thermal coupling to the bearing, without compromising the bearing structure itself with mounting holes or other modifications. Each module includes vibration, load, and temperature sensors, data acquisition, a microcontroller, and an RF communication subsystem. The design of the electronics and embedded software will be done from the component level at UTRGV to meet stringent requirements on timing, accuracy, and power consumption, and will be the largest portion of the project.

The eight sensors will be managed by a hub. In long-term field deployment, this would be another custom module designed to mount on the side or roof of the railcar. In the first year, the hub will be a commercial off-the-shelf (COTS) computer supplemented with communication and location sensing modules, running dedicated software that we will develop. Communication will be via LoRa, controlled directly at the packet level *without* any higher-level network protocol (e.g., no LoRaWan) to avoid uncontrolled latencies. This direct control will allow the use of broadcast packets for synchronization and addressed peer-to-peer packets for command and data collection.

For the first year our focus will be hardware and software development and rigorous testing of timing and accuracy. However, to get a head start on the data analysis, one branch of the project will examine existing and simulated data sets using machine learning techniques. The first-year objective of this effort will be to automatically separate wheel, track, and coupling defects offline, with the eventual goal of real time detection at the hub level in later phases of the project.

E.5 DESCRIPTION OF TASKS TO BE COMPLETED IN RESEARCH PROJECT

Task 1: Wireless Sensor Hardware

a. Electronic Design: Design objectives include (a) addressing issues found during previous generation systems, (b) increasing resolution while reducing noise, and (c) adding precision time synchronization with other sensors. For parts (a) and (b) we will modify the power system to eliminate switching power conversion, use higher performance analog-to-digital converters (ADCs), and add flexibility to our pre-ADC filtering. Part (c) requires changing from the current BLE (Bluetooth Low Energy) wireless to LoRa for more granular control over packet timing. This change will also allow on-the-fly tradeoff of reporting frequency and packet size versus battery consumption, and longer-range communication at low power.

b. Design Review: Prior to finalizing the design for fabrication, we will conduct a design review with input from selected stakeholders. Internal reviewers will focus on circuit level issues, while the external reviews will focus on expected performance targets and system level architecture.

c. Fabrication & Testing: We plan to construct at least 20 modules to prepare for a single car field deployment (8 sensors), full instrumentation of two laboratory four bearing testers (8 sensors), plus spares.

Task 2: Data Collection Hubs

a. Platform Selection: For first-year lab testing and short-term field tests on a designated car, where larger batteries and shorter battery lives are acceptable, we will use COTS components including a compact computer, communication and GPS dongles, and battery pack. Control of and data collection from the wireless sensors will be via a LoRa dongle. User collection of data from the hub will be primarily via removable storage devices, with

Wi-Fi available as an alternative in the lab, and GSM for monitoring and data summaries when on board a railcar.

b. Hub System Integration: An integrated data acquisition application for the hub will be developed that includes the following features: (a) both user console and autonomous modes, (b) ability to control 16 sensor modules either in simultaneous broadcast mode for synchronization or individually for data collection, (c) data archiving onboard, (d) first level data analysis to obtain statistical parameters and recognize outlier events.

Task 3: Embedded Software

a. Software Design: Our earlier generation wireless module uses a microcontroller reliant on a built-in RTOS (real time operating system) including a BLE communication stack. While this system had advantages for rapid development, it complicates precision timing of communications, which in turn degrades synchronization of sampling and widens receiver power-on windows. The new architecture will use a smaller processor with advanced low power features, bare-metal programming, and timing driven by hardware interrupts rather than RTOS messaging.

b. Design Review: Like the hardware, the software will be subject to a design review by local UTCRS personnel, and external reviews with selected stakeholders. The external reviews will be focused on expected performance targets and standards selected for communication packet content and parameters.

Task 4: Foundations for Automated Data Analysis

a. Algorithm design: The first objective is to model the detection and prediction task using machine learning methods with data obtained from Task 2. The machine learning methods selected here are the nonparametric kernel methods, which are universal and can approximate any nonlinear functions [4]. Moreover, kernel methods-based machine learning algorithms do not require large dataset, making it attractive for online and adaptive implementation in the future. The second task is to reduce the computation complexity of kernel-based learning with the random feature mapping technique. This is because the traditional kernel methods, although effective, are not scalable to large dataset's size. With the random feature approximation, the analysis complexity will be fixed and does not increase with dataset's size [5, 6].

b. Design review: Prior to deploying the designed algorithm in testbed, we will review the effectiveness of the algorithms with both simulated and real data obtained from Task 2.

The effectiveness of the algorithm will be evaluated with the detection accuracy, prediction accuracy, false positive rate, etc.

Task 5: Documentation, Dissemination, and Transfer

The PIs and UTCRS understand that the utility of our research depends entirely on documenting our work and making it available to DoT, industrial partners, and future researchers. We are committed to: (a) meeting all DoT and internal reporting requirements, (b) archiving all data and documents, (c) publishing key results in conferences and journals read by rail transport researchers and practitioners, and (d) working with industry and our Office of Technology Commercialization to create opportunities for field tests, licensing, and other collaborations.

E.6 EXPECTED RESULTS AND PRODUCTS (PROJECT DELIVERABLES)

The expected products and deliverables include:

a. A set of working hardware prototypes for next generation wireless sensors.
b. Design files for the prototypes including schematics, layout, assembly instructions, and bill of materials, in format compatible with open-source EDA tools.
c. A working integrated prototype for a data collection hub suitable for both lab and test car use. The laboratory/testbed version will be based on commercial modules.
d. Embedded software for the sensor prototypes, documented and archived, using only bare metal code and open-source libraries, in format compatible with free IDE tools.
e. Software for the data collection hub, documented and archived.
f. Sample raw and processed datasets from test runs on laboratory bearing testers, annotated with information on test conditions and bearing conditions. These datasets will be archived and available for potential collaborators upon request.
g. Preliminary machine learning methods with experiment results that demonstrate the success of automated data analysis.
h. Final report including any DoT or UTCRS required information.
i. One or more conference or journal publications. At a minimum we will submit to the Spring 2024 Joint Rail Conference (JRC) with intermediate results.

E.7 TECHNOLOGY TRANSFER IMPLEMENTATION PLAN

UTRGV's Office of Technology Commercialization (OTC) assists PIs with evaluating patentability and providing support for the entire application process for any inventions identified. They also provide support for negotiating technology transfers and industry contracts. With the help of the OTC, the PI and co-PI already have a granted patent, an ongoing licensing agreement with one manufacturer, Hum Industries, and perform contract bearing testing for multiple other manufacturers.

Our plan is to extend these industry relationships by: (a) continuing work with our existing partners, (b) offering our improved in-house measurement and diagnostic capabilities to all manufacturers of bearings, adapters, and related components, and (c) seeking opportunities for field deployment of our system after the completion of this initial phase. Finally, through publication in rail-oriented conferences and journals, we will make practitioners directly aware of our progress and key results.

E.8 PROJECT BROADER IMPACT(S)

The research itself, as well as the training of engineering students, will have impacts beyond the immediate usage of the sensors to avert accidents and enable proactive maintenance. **Research Activities:** As stated earlier, the next generation of sensors, when deployed in the field, will produce data about railcars and track of type and quality that have not been previously available. Both industry and academic professionals will be able to conduct their own investigations and use the data in ways the current PIs have not yet contemplated. Our previous generations of wired and wireless sensors each generated multiple independent projects and publications using the data produced. **Educational Activities:** As a minority serving institution in rapidly growing metropolitan area, we anticipate that most of the students will be from underrepresented groups and that a good fraction of them will contribute to industrial development in the region. The project budget itself supports two students who will gain experience in developing rail-specific electronics and software, as well as bearing test equipment. The sensor platform will also enable several other students to be trained in the use of the system and its data for independent research projects on mechanical, thermal, and operational aspects of railcar and track performance. We anticipate that at least eight students will participate in various aspects of the project.

E.9 TIMELINE (GANTT CHART)

	6/23 – 7/23	8/23 – 9/23	10/23 – 11/23	12/23 – 1/24	2/24 – 3/24	4/24 – 5/24	6/24 – 7/24
Task 1: Electronics Design							
Task 1: Design Review							
Task 1: Fabrication							
Task 2: Platform Selection							
Task 2: System Integration							
Task 3: Embedded Software							
Task 3: Design Review							
Task 4: Automated Analysis							
Task 4: Design Review							

Task 5: Dissemination and Technology Transfer							

F. DISCUSSION OF PERTINENT COMPLETED RESEARCH AND RELATED RESEARCH IN PROGRESS

This project will build on several years of previous work at UTCRS by the PI and second co-PI. This includes work on both wired and wireless sensors, years of data collection, and optimization of detection algorithms using Fourier domain techniques [7,8]. In particular, the previous generation of sensors developed at UTCRS (Figure 2, left) demonstrated several positive outcomes: demonstrated success in detecting defective bearings and in distinguishing cone and cup from each other, and reliable operation over a period of several months. They also demonstrated limitations which must be overcome: a three-month battery life when operated continuously, limited communication range, fragility during mounting, and most importantly, accuracy that is usable but not as good as the best results from wired sensors using an instrumentation grade data acquisition system. The reduction is accuracy has been traced to reduced sample lengths and resolution, which we intend to overcome in the next generation of modules. These results will inform our future work.

The project also builds on our ongoing work with Hum Industrial, who are deploying their own version of a wireless sensor (Figure 2, right) with parts of the development and testing conducted in our labs. This work has demonstrated that battery life can be extended indefinitely with the use of thermoelectric energy harvesting, that LoRa protocols give extended range and better control of power consumption, and that sensors can be made robust enough for long term mounting on a rail car [2]. They have also shown in field trials that the same sensor suite we use to detect bad bearings is capable of separately identifying damaged wheels and damaged track.

In related work, we have investigated thermoelectric harvesting of heat generated within the bearing and transferred to ambient through the bearing adapter [10,11]. An example can be seen in the right side of Figure 2. This work, which is ongoing [12], has demonstrated that thermoelectric modules are more than sufficient to power a

LoRa sensor that is activated once every ten minutes, when combined with energy storage and mounted on a railcar with typical distribution of speeds and loading.

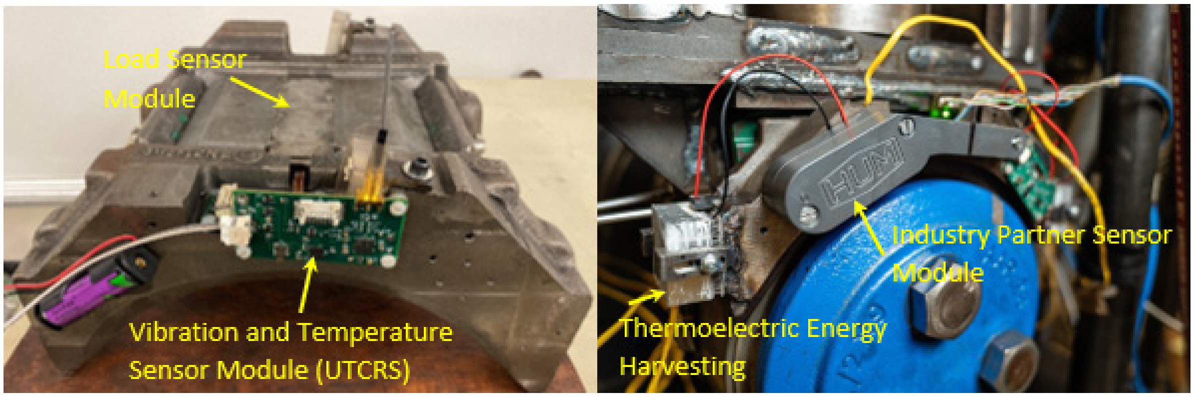

Figure 2: (Left) Previous generation UTCRS sensors (Right) Commercial sensor produced by HUM, our industry partner.

G. KEY WORDS

Railway Safety, Railway Bearings, Bearing Condition Monitoring, Sensor Fusion, Machine learning, Kernel methods, Random Feature Mapping.

H. LITERATURE CITED

[1] J. Lima, C. Tarawneh, J. Aguilera, and J. Cuanang, "Estimating the Inner Ring Defect Size and Residual Service Life of Freight Railcar Bearings Using Vibration Signatures," ASME Joint Rail Conference, Online, Virtual, April 19-22, 2020.

[2] M. Barrera, L. Cantu, C. Tarawneh, H. Foltz, B. Wilson, and B. Porter, "Pilot Field Test of an Onboard Wireless Health Monitoring System for Railroad Rolling Stock," ASME Joint Rail Conference, Online, Virtual, April 20-21, 2022.

[3] L. Villafranca, M. Noruzoliaee, C. Tarawneh, and A. Sanchez-Trinida, "Predicting the Remaining Service Life of Railroad Bearings: Leveraging Machine Learning and Onboard Sensor Data," ASME Joint Rail Conference, Online, Virtual, April 20-21, 2022.

[4] T. Hofmann, B. Schölkopf, and A. J. Smola, "Kernel Methods in Machine Learning," (2008): 1171-1220.

[5] A. Rahimi and B. Recht, "Random Features for Large-Scale Kernel Machines," Advances in Neural Information Processing Systems, 20, (2007).

[6] P. Xu et al., "COKE: Communication-Censored Decentralized Kernel Learning," Journal of Machine Learning Research, 22.1, (2021): 8813-8847.

[7] J. Cuanang, C. Tarawneh, M. Amaro, J. Lima, and H. Foltz, “Optimization of Railroad Bearing Health Monitoring System for Wireless Utilization,” ASME Joint Rail Conference, Online, Virtual, April 19-22, 2020.

[8] C. Tarawneh, J. Lima, N. De Los Santos, and R. Jones, 2019. Prognostics models for railroad tapered-roller bearings with spall defects on inner or outer rings. Tribology Transactions, 62(5): 897-906.

[9] N. De Los Santos, C. Tarawneh, R. Jones, and A. Fuentes, “Defect Prognostic Models for Spall Growth in Railroad Bearing Rolling Elements,” ASME Joint Rail Conference, Pittsburgh, PA, April 18-20, 2018.

[10] M. Amaro, C. Tarawneh, H. Foltz, and R. Aguilera-Toro, “Performance of a Thermoelectric-Based Energy Harvesting Device on a Realistic Railroad Route,” ASME Joint Rail Conference, Online, Virtual, April 20-21, 2022.

[11] H. Foltz, C. Tarawneh, M. Amaro, S. Thomas, and D. Capitanachi-Avila, “Thermoelectric Energy Harvesting for Wireless Onboard Rail Condition Monitoring,” International Journal of Rail Transportation, April 2023. (https://doi.org/10.1080/23248378.2023.2201247)

[12] D. Capitanachi-Avila, K. Quaye, C. Tarawneh, and H. Foltz, “Effect of Heat Sink Positioning on the Viability of Thermoelectric Energy Harvesting on Railcar Bearing Adapters,” JRC2023-105034, ASME Joint Rail Conference, Baltimore, MD, April 11-13, 2023.

I. STAFFING PLAN & PROJECT MONITOR

Personnel The project personnel directly supported will include three faculty, one graduate student, and one undergraduate student. One more graduate student supported from non-federal cost share funds will also participate in the project.

The PI, Heinrich Foltz, will be budgeted for one month during the summer, and will contribute 15% of his time during the regular academic year as cost share. He will focus on design of electronics and embedded software.

The first co-PI, Ping Xu, will be budgeted for one month during the summer, and will contribute 15% of her time during the regular academic year as cost share. She will focus on applying machine learning to sample data sets in preparation for the next phase of the project. The second co-PI, Constantine Tarawneh, will be budgeted for ¼ month during the summer, and will contribute 5% of his time during the regular academic year as cost share. He will focus on technology transfer, alignment of system specifications with industry needs, and on design and execution of laboratory testing.

The students on the project will assist in electronic design, fabrication, laboratory testing, and software development. It is anticipated that the two graduate students will derive part or all of their master's thesis from this project.

Project Monitor The budgetary aspects of the project will be monitored by the UTCRS Program Coordinator with further monitoring and supervision by the UTRGV Office of Research. The research aspects of the project will be monitored by the UTCRS Director, the UTCRS Executive Committee, and the UTCRS External Advisory Board.

J. BUDGET JUSTIFICATION & MATCHING FUNDS DETAILED INFORMATION

CATEGORY	Budgeted Amount from Federal Share	Budgeted Amount from Matching Funds	Explanatory Notes
Faculty Salary	$ 32,750	$ 40,200	**Federal:** One month for the PI, one month for the first Co-PI, and ¼ month for the second Co-PI **Match:** 15% of time and effort during the regular academic year for the PI and the first Co-PI, and 5% for the second Co-PI.
Research Assistants	$ 33,150	$ 18,750	**Federal:** One graduate research assistant at $1250/month for 15 months, and one undergraduate research assistant at $960/month for 15 months. **Match:** Graduate research assistant at $1250/month for 15 months
Faculty and Student Fringe Benefits	$ 9,210	$ 11,523	**Federal:** Faculty benefits at 18% for the summer months, and student benefits at 10%. **Match:** Faculty benefits at 24% during regular academic year, and student benefits at 10%.
Permanent Equipment	$ -	$ -	**Federal:** None. **Match:** None.
Expendable Property, Supplies, and Services	$ 3,000	$ -	**Federal:** Parts needed for fabrication and validation of testbed. **Match:** None.
Domestic Travel	$ 1,600	$ 1,600	**Federal:** Travel costs to present research findings at conferences.

			Match: Travel costs to present research findings at conferences.
Total Direct Costs	$ 79,710	$ 72,073	
F&A (Indirect) Costs	$ 38,261	$ -	**Federal:** Indirect cost rate at 48% of total direct costs. **Match:** None.
Total Costs	**$ 117,971**	**$ 72,073**	