MODULAR DAMAGE DETECTION FOR EXPANDABLE STRUCTURES

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Agenda

- Background
- Sensor System Design
- Sensory Panel
- Embedded Software
- Graphical User Interface
- Testing and Demonstration
- Summary
- Questions & Answers

Background

- Micrometeoroids (MM) & Orbital Debris (OD) are serious threats to International Space Station (ISS) & extraterrestrial habitats
  - NASA classes MM & OD as primary threats to commercial crew vehicles
    - See article at https://www.nasaspaceflight.com/2016/08/nasa-mmod-primary-threat-crew-vehicles/
  - In July 2014, radiator damage was observed after review of downlinked camera inspection imagery
    - See article at http://www.nasaspaceflight.com/2014/07/iss-managers-evaluating-mmod-radiator/)
- NASA has identified structural health monitoring and damage detection technologies as critical needs in multiple technology roadmaps

Background

- NASA Kennedy Space Center (KSC) has been developing damage detection technologies for years
  - U.S. Patent 9,233,765 & 9,635,302,B2

- KSC has successfully tested and demonstrated damage detection technologies
  - In 2011, demonstrated single panel system for Habitat Demonstration Unit (HDU) field demonstration at Desert Research and Technology Studies (D-RATS)
  - In 2012, integrated and demonstrated damage detection system with multiple sensory panels in crew display avionics for HDU
  - In 2013, demonstrated remote testing capability of three panel system using a secure network (between KSC & JSC)

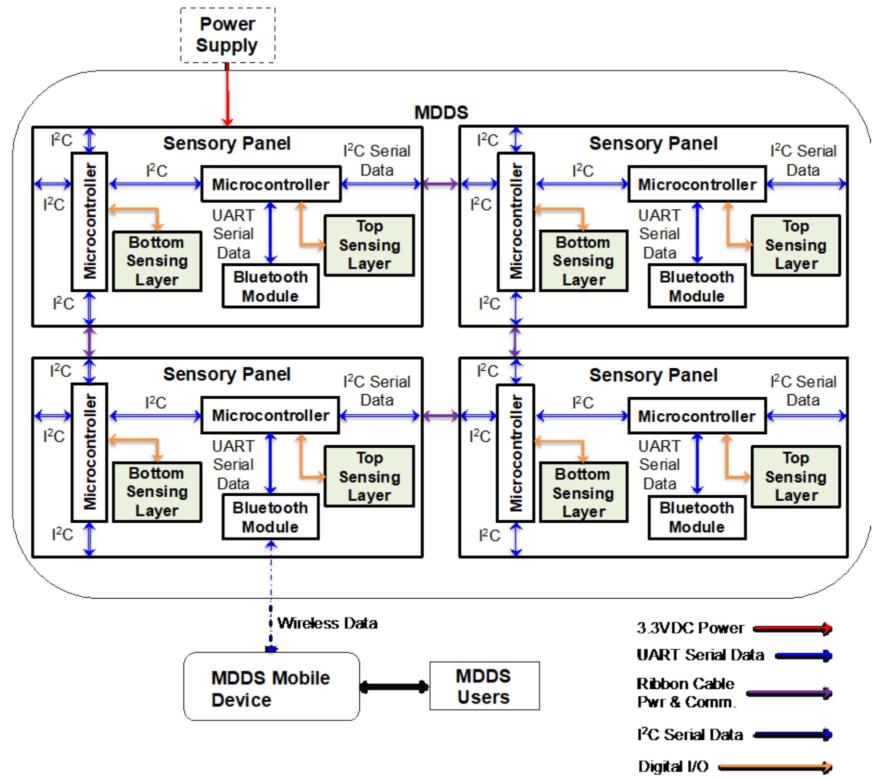
Sensor System Design

- Modular Damage Detection System (MDDS) is an intelligent damage detection “skin” that could be embedded into or added to structures
  - Technology based on sensing electrical integrity of parallel conductive traces
    - When an impact occurs, traces are broken
  - Several sensing layers can be implemented, where alternate layers are arranged orthogonally with respect to adjacent layers
  - Design is tailorable for interior and/or exterior applications
    - Sensing panel material, size, and trace spacing can be customized per application
  - Provides lightweight in-situ health monitoring capability for spacecraft or expandable, deployable structures

- MDDS consists of three main subsystems
  - Sensory Panel(s)
  - Embedded software for situational awareness and damage detection
  - Mobile device with graphical user interface (GUI) to operate the system

Sensor System Design

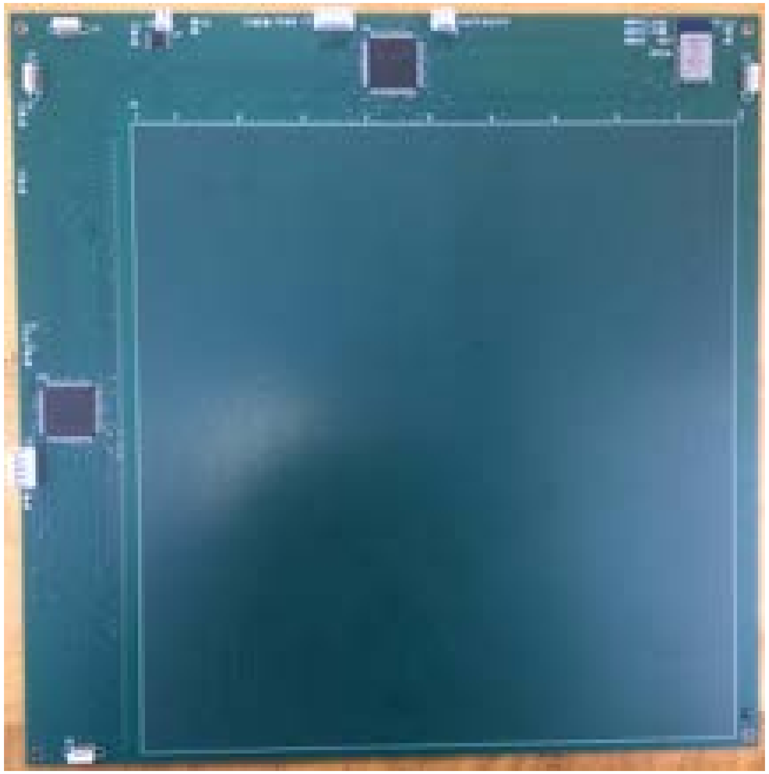
- MDDS architecture is flexible and expandable, supporting one or many Sensory Panels organized two-dimensionally in grid pattern
  - Sensory Panels are identical in hardware & software which greatly enhances modularity
  - They are interchangeable and operate independently, scanning for damage periodically and waiting to be connected to a Bluetooth-enabled device
  - GUI on the mobile device allows users to configure, command, and monitor the Sensory Panels in the system



Notional MDDS Architecture Block Diagram with Four Sensory Panels

Sensory Panel

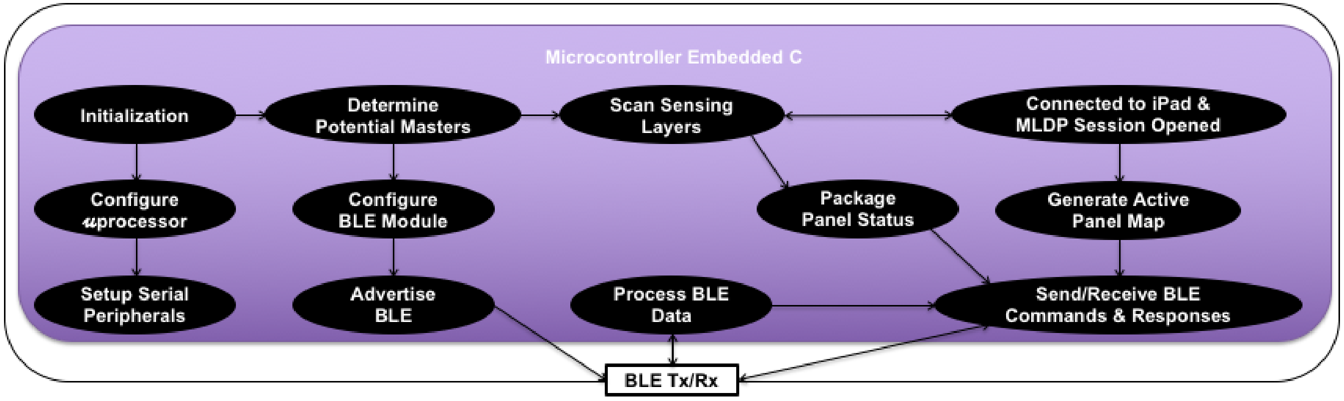
- Sensory Panels consist of two 32-bit microcontrollers with embedded software, two Sensing Layers, and Bluetooth low-energy (BLE) module for wireless communication
  - Two serial peripheral interfaces (UART & I^2C) for communication
  - Each Sensing Layer has 96 parallel conductive traces with trace-to-trace spacing of approximately 50 mils
  - Sensing Layers are oriented orthogonally creating a two-dimensional grid pattern
  - Sensory Panel overall dimensions are 9.5 x 9.5 x 0.062 in. (W x L x D)
    - Sensing Layers are 7.67 x 7.67 in.
  - Low power consumption – typically less than 500mW / panel



MDDS Sensory Panel

Embedded Software

- Embedded software is stored in non-volatile memory of microcontrollers
  - Initializes and configures the serial peripheral interfaces and the BLE module
  - Processes and responds to commands sent from the mobile device and reports Sensory Panel health information upon request
  - Executes algorithms to:
    - Determine potential Master Panels (MPs) and set the MP upon connection with GUI
    - Generate active panel map
    - Monitor the health status of all active panels



Sensory Panel Embedded Software Logical and Structural Overview

Embedded Software

- Each panel checks presence of an active panel to its left and/or below it using I^2C serial interfaces to determine potential Master Panels (MPs)
  - If no active panels are present to left or below, it assigns panel as potential MP and configures BLE module
  - Since configuration of MDDS is arbitrary, one or more potential MPs could be present
- User selects a MP arbitrarily using the GUI
  - Once assigned, all other panels become normal, active panels

- Newly-assigned MP starts a progressive scan using active panel mapping algorithm to determine spatial relationship to the other active panels
  - Communicates with adjacent panels to determine its closest neighboring panels
  - Requests each of its adjacent neighbors to report status of their respective neighbors until no new panels are found
  - Maintains a record of the configuration and path to access any active panel

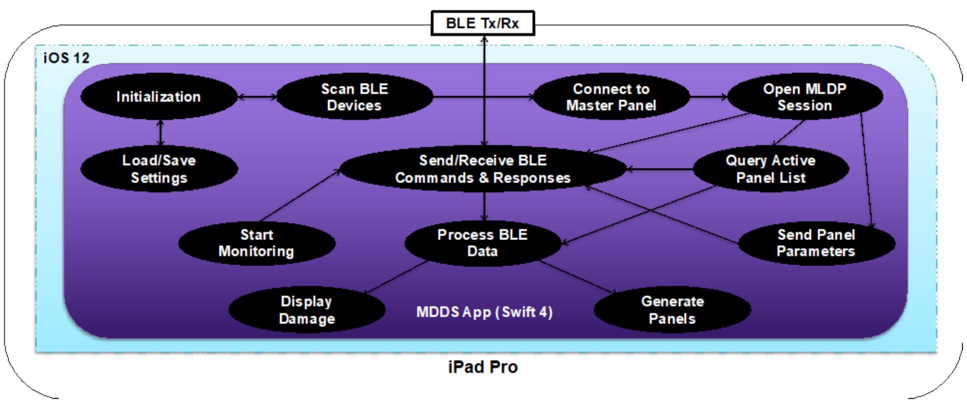
Embedded Software

- Each Sensory Panel continuously monitors its health
  - Damage detection algorithm evaluates health status by injecting test pulses periodically on the sensing traces to determine the electrical integrity
    - If traces are broken, algorithm calculates actual location of any faults
    - Relative time stamp is associated with each damage event to establish proper order of events
      - Helps organize and identify the location of damage if subsequent damages occur at a later time on the same panel

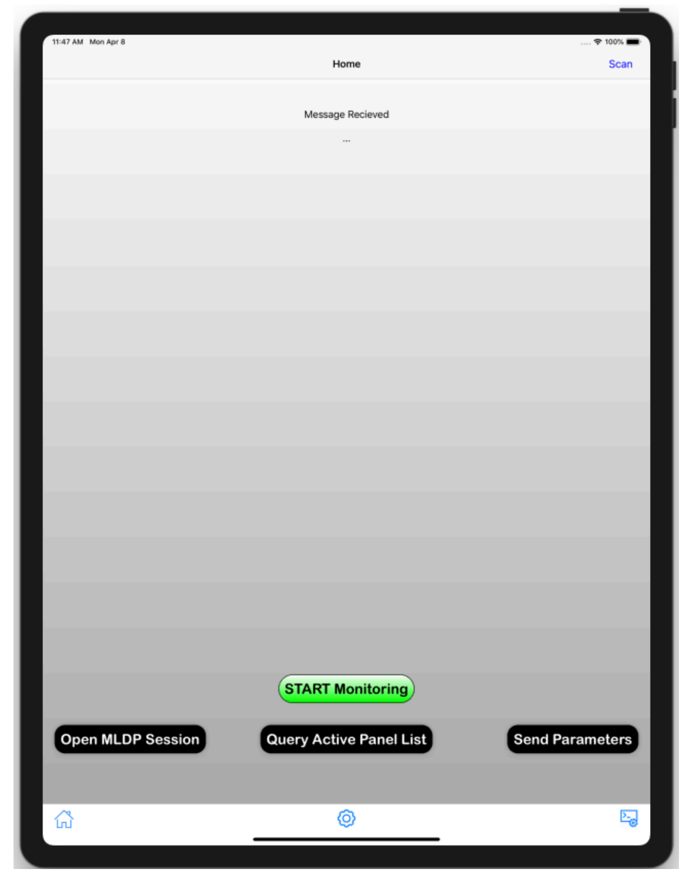
- GUI periodically requests health status from MP of all active panels
  - MP gathers, coordinates, and packages damage information and sends it wirelessly to the GUI
    - Damage location is reported in rectangular boundaries (bottom left-hand to upper right-hand corners)
    - When damage is detected on top Sensing Layer ONLY, exact damage location is undermined
      - Reports the corresponding location in the x-axis only

MDDS GUI

- MDDS application (app) designed for 3rd generation iPad Pro with iOS 12
  - Written in Swift 4.2 using Xcode 10
  - GUI allows users to configure, command, control, monitor, and display health status of active Sensory Panels in the system
  - Receives telemetry wirelessly from MP using Bluetooth technology



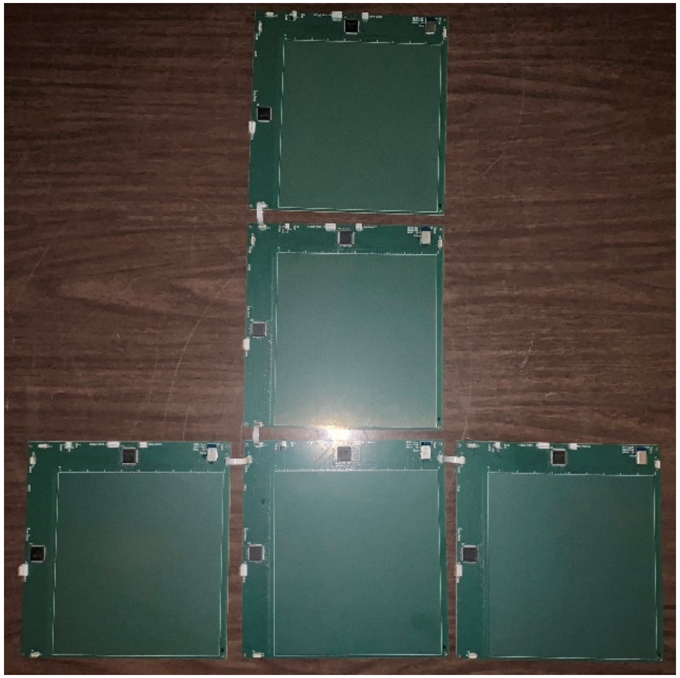
MDDS App Software Logical and Structural Overview



MDDS Application Home Page

Testing & Demonstration

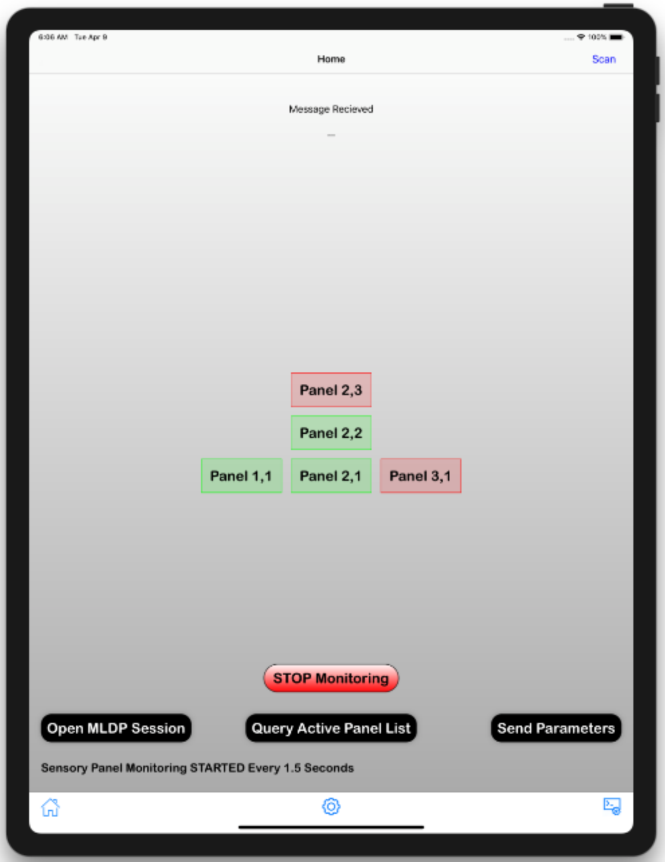
- Simulated test data was created to evaluate MDDS App performance
  - Data set consisted of five Sensory Panels laid out in an inverted-T pattern
- Upon power-up, Sensory Panels performed their initialization and determined whether they're a potential MP
- User scans for BLE advertisements and selects potential MP
  - Upon connection, MP is assigned
- User configures Sensory Panel settings and opens BLE private communication service to send and receive information wirelessly



Sensory Panels Layout for Simulated Testing

Testing & Demonstration

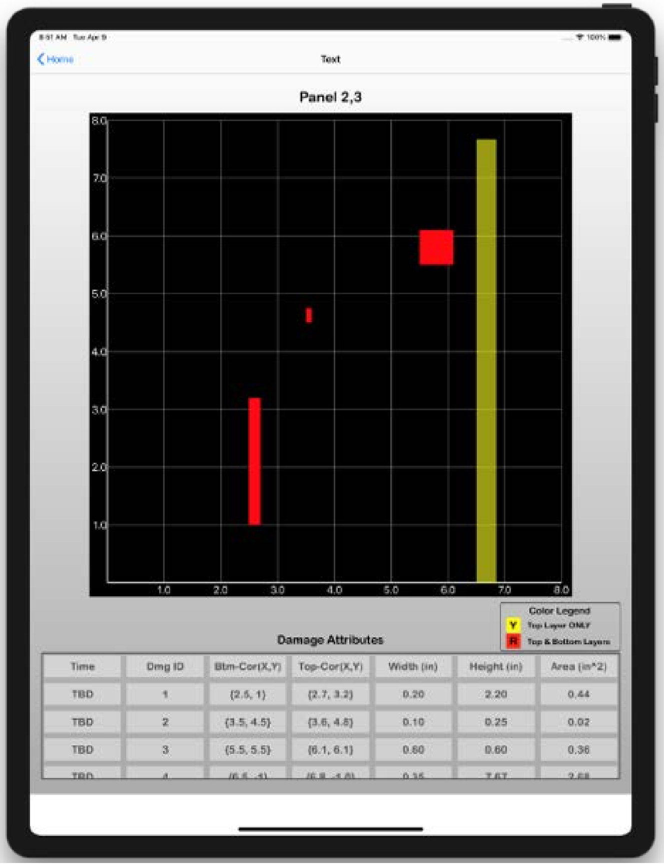
- Using the GUI, user requests query of active panels from MP and begins monitoring the system
- Two of the five Sensory Panels simulated health status contain damage information for display
  - Sensory Panels' graphics with red backgrounds and borders indicate panels with damage
  - Green-filled panels indicate Sensory Panels without damage
- Panel IDs increment from bottom left to top right
- Detailed Sensory Panel health information is displayed by clicking on the panel graphic



GUI Displaying Active Sensory Panels & Their Health Status

Testing & Demonstration

- Panel 2,3 GUI shows four simulated damage areas:
  - Three rectangular/square in red
    - Damage resulting in broken conductive traces on both top and bottom Sensing Layers
  - One top-only damage in yellow
    - X-only coordinate provided; no y-coordinate can be assigned
- Damage details are displayed in tabular format
  - Damage ID number is assigned
  - Bottom left-hand corner and top right-hand corner x- and y-coordinates are shown
  - Damage width, height, and calculated area are displayed



Detailed Damage Information for Panel 2,3

Summary

- NASA KSC has been developing and successfully demonstrating damage detection technologies for years
- MDDS provides an attractive option for applications where in-situ health monitoring for space debris impacts is needed
  - Design is tailorable for interior and/or exterior applications
  - Architecture is flexible and expandable, supporting one or many Sensory Panels
    - Algorithms provide for situational awareness, self-configuration, and damage detection and localization
    - Supports wireless communication using Bluetooth technology
  - Sensory Panels are modular and interchangeable
    - Same hardware and software
    - Low power consumption – typically less than 500mW / panel
  - MDDS App provides users a simple and attractive method to interact with the system

Questions