How to Build a Rover: An Overview of the Mars 2020 Mission's Vehicle System Testbed

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***Abstract*—While NASA's Mars rover Perseverance continues to make groundbreaking achievements on the Red Planet, its twin is hard at work here on Earth. The Operational Perseverance Twin for the Integration of Mechanisms and Instruments Sent to Mars, or OPTIMISM, is the Mars 2020 Vehicle System Testbed (VSTB) rover operated by NASA Jet Propulsion Laboratory (JPL) in Pasadena, California. OPTIMISM's home is the JPL Mars Yard; an outdoor field with red soil that simulates the terrain encountered by Perseverance. The VSTB is a full-scale engineering model of the flight rover, serving a number of functions to ensure mission operations can continue smoothly and on schedule. The VSTB possesses instrumentation, computers, mechanisms, cameras, and a Mobility subsystem that are nearly identical to its extraterrestrial twin. Its high fidelity allows the rover to be a highly effective tool to fully test system functionality and performance prior to commanding the flight rover.**

The early stages of building OPTIMISM began a few months prior to Perseverance departing JPL for Cape Canaveral, FL in early 2020. Electrical integration of the flight system avionics, and compatibility checkouts of the electrical ground support equipment ensured that the foundation of the electrical system was operational and in place. Next, the internal harnessing was installed and compatibility checks of the rover instrumentation and mechanisms were performed to confirm the system was prepared for full buildup. Finally, mechanical assembly of the rover chassis with its external components completed the integration of the system before it was moved to the Mars Yard for its initial phase of testing to perform verification & validation (V&V) of the Mobility subsystem requirements.

By the time Perseverance landed at Jezero Crater in February 2021, the first phase of VSTB operations was underway. Surface guidance, navigation, and control (SGNC) testing for the Mobility subsystem ensured functionality and performance requirements were met for various capabilities such as visual odometry (VO), mapping, and automatic navigation (AutoNav). Subsequent integration of the robotic arm (RA) onto the VSTB enabled the V&V campaign for surface sampling operations (SSO) to commence. As the mission's engineering operations (EO) have gotten underway, the VSTB has been utilized for an array of purposes including troubleshooting software anomalies, and performing dry-runs for first time activities (FTAs) prior to sending the commands to Perseverance. OPTIMISM will continue to serve mission critical functions as long as Perseverance is roving the Red Planet.

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1. INTRODUCTION

As space exploration missions grow progressively more complex, the need for advanced testing methods increases. The array of system requirements that must be validated for these missions requires extensive testing beyond what can be achieved with the flight hardware alone. Testbeds provide a separate venue for the project to validate the flight system outside of the flight vehicle schedule. With this arrangement, testbed engineers can work independently of the systems engineers that build the spacecraft. Additionally, requirements may be verified using testbeds in such a way that the flight hardware is not compromised or endangered.

WHAT IS A TESTBED?

Testbeds are laboratory environments that are designed to imitate a control system. In avionics systems, testbeds are usually composed of one or more parts of the core control hardware and are used to study each system component and their interactions. Testbeds are typically built from prototypes or engineering model hardware, and are designed in such a way that they only focus on a specific subset of the total system. For the Mars 2020 Project (M2020), all the main

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testbeds utilize the core avionics, including the main flight computer. Each testbed has a distinct purpose; used for different phases of the Mars 2020 mission from launch, to landing, to surface operations and beyond.

The testbed provides a space for integrating newly developed functions of the system so the subsystem interactions can be recorded, evaluated, and understood. Outside of the core avionics, simulated hardware is used to mimic analog or digital signals that would typically come from the spacecraft. An interface is used to provide real-time or simulated data from the system once fully developed. Finally, testbeds allow for systems engineers to make design decisions based on both simulated and real-world observation, with the goal of developing, optimizing, and perfecting the system's control architecture (e.g., hardware or software).

WHY DO WE NEED A TESTBED?

The Mars 2020 Perseverance Rover has seven different instruments onboard to perform science objectives on the surface of Mars. Additionally, the rover possesses a Mobility subsystem based on MSL's heritage design; a large suite of engineering cameras (2 Navigation Cameras, 4 Front Hazard Cameras, 2 Rear Hazard Cameras); and a Robotic Arm (RA) with a drill that interfaces with a sampling and caching system. The full list of science instruments is listed here (NASA, n.d.):

- Radar Imager for Mars' Subsurface Experiment (RIMFAX)
- SuperCam
- Mastcam-Z
- Mars Oxygen ISRU Experiment (MOXIE)
- Mars Environmental Dynamics Analyzer (MEDA)
- Planetary Instrument for X-ray Lithochemistry (PIXL)
- Scanning Habitable Environments with Raman & Luminescence for Organics and Chemicals (SHERLOC)

These science instruments are state-of-the art tools used to acquire new information about the Martian geology, atmosphere, environmental conditions, and potential biosignatures.

Each instrument can run their own version of software, but is primarily controlled by the Rover Compute Element (RCE) which can be considered the "brain" of the rover. The RCE is mainly responsible for monitoring the health of the spacecraft and is programmed with a number of contingency protocols in the event that an anomaly occurs during daily operations. The RCE also houses the internal memory of the rover and is responsible for receiving commands from Earth, storing data from the executed commands, and sending that data back to Earth.

The execution of commands to each instrument is performed through a complex series of events. Once a command is sent across millions of miles of space from Earth to Mars and reaches the rover's high-gain antenna, the RCE processes the command package, sends its own command to the Rover Power and Analog Module (RPAM) to provision power to the device, then waits for data to be returned from the commanded device. Once the commanded device is switched on, it will initialize its own software and continue to receive commands or send additional data to the RCE.

The Mars 2020 spacecraft is the most complex system to ever operate on the Red Planet. The rover's subsystems are tested in their individual lab environments using box-level tests, but a System Testbed is necessary to provide the highest level of confidence in the testing of system-wide interactions.

WHAT MAKES UP A TESTBED?

Testbeds comprise a mixture of real avionics hardware and simulated hardware. To be able to simulate the core flight system, an M2020 testbed will always possess at least one RPAM and at least one RCE. For testbeds that require activating mechanisms, like motors on the RA or Mobility actuators, the Rover Motor Controller Assembly (RMCA) is required. Any external instrument (i.e., from the list above) is mated to each of these core avionics boxes.

While the goal of the testbeds is to closely mimic the system, this is not always possible due to hardware and budget constraints. Most Systems Testbeds include Simulation and Support Equipment (SSE) racks that simulate the specific software environment of the spacecraft that cannot be integrated into the testbed. Certain aspects of the flight system like the Radioisotope Thermoelectric Generator (RTG), which provides the rover its power, cannot be tested in an open laboratory here on Earth due to personnel safety considerations. Instead, the power enters the spacecraft from a set of power supplies that provide the same voltage and current characteristics of the RTG. Similarly, most Platinum Resistance Thermometers (PRTs) present on the flight rover, used to constantly measure the temperature of instruments and sensors, are not integrated into all of the testbed hardware. Most of the rover's PRTs are absent because the testbed components will not be operated in the severely cold Martian environment, and therefore will nominally fall well outside of the expected thermal bounds. Certain power and thermal signals are simulated to trick the spacecraft into believing these values are within nominal limits.

While SSE allows us to "trick" the system into believing it is functioning normally in space, there is also hardware implemented into the testbeds to facilitate testing here on Earth. Ground Support Equipment (GSE) permits the team to uplink commands while simultaneously allowing downlink of the current status of the testbed to users. Lastly, testbeds are also built with a large data storage network in place to allow for archival and easy access of test data across years of development and verification.

The combination of GSE and SSE allows for various

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commands to be sent or analog/digital signals to be adjusted within the spacecraft to stimulate specific system responses. Interfaces for all instruments are built with enough fidelity to be used to perform subsystem-level and systems-level end-to-end verification. For instance, the testbed can verify if a low voltage detected within an instrument will prompt the correct response downstream of the instrument at the RCE.

THE M2020 SYSTEM TESTBEDS

All space missions require testing capabilities to ensure mission success. In general, System Testbeds support four primary functions:

1. Verification and validation (V&V) of Level 3 (i.e., system level) project requirements
2. Dry run tests and activities prior to execution on the flight vehicle
3. Operations team training
4. Anomaly debug.

For the Mars 2020 project, three testbeds were designed to achieve these four functions and facilitate testing across the different phases of the mission:

1. The Mission System Testbed (MSTB), where simulated instruments on the Cruise and Descent Stages are put together, is used primarily to simulate the Cruise phase and Entry, Descent, and Landing (EDL) sequence.

2. The Flight Software Testbed (FSWTB) is used to test mechanisms and instrument interfaces. This testbed utilizes a large metal chassis called the Hexapod, whose name refers to its six hydraulic legs that can be adjusted to orient the instrument chassis as needed. Using the Hexapod, the testbed team can mount various mechanisms like the Robotic Arm and the Remote Sensing Mast to achieve more flight-like configurations. The chassis can be adjusted at various degrees of tilt to test the system.

3. The Vehicle System Testbed (VSTB) is used to test the entire system in the highest-possible-fidelity configuration. This testbed features a full Mobility subsystem and is almost an exact copy of the Perseverance Rover. Following the Full Build, the VSTB includes the full suite of instruments and the sampling and caching system identical to the flight rover.

The System Testbed capabilities span all phases of the mission. Prior to the existence of the VSTB, the other two Mars 2020 System Testbeds provided testing for Launch, Cruise, EDL, and the surface sampling portion of the Rover phase. The VSTB provides the System Testbed capability to test Mobility.

WHY THE VSTB NEEDED TO BE BUILT

Mars 2020 inherited much of its design from the Mars Science Laboratory (MSL) mission. MSL built its own set of System Testbeds to test its Launch, Cruise, EDL, and Rover phases. These testbeds were the MSTB, FSWTB, and MSL's own VSTB. MSL's MSTB and FSWTB tested MSL Launch, Cruise, EDL, and the surface sampling portion of the Rover phase. MSL organized these stationary System Testbeds on racks and table tops, which made the electronics and cabling accessible. MSL's VSTB is the engineering model for the Curiosity rover, meaning it's an accurate replica that provides full system fidelity for all the testbed functions stated above. Like the Curiosity rover, MSL's VSTB mounts the internal electronics inside the chassis on the Rover Avionics Mounting Plate (RAMP). The RAMP is mounted to the rover top deck. The internal electronics mount to the RAMP with the mounting interface pointing up. Below the electronics the internal cabling, or harnessing, connects the internal electronic components to each other and to the external electronics. Unlike the stationary System Testbeds with easily accessible electronics, the MSL VSTB requires support equipment to open the chassis and access the internal electronics. The effort to reach the internal electronics is large. Consequently, the System Testbed team plans the VSTB build to minimize the number of times the team must open the chassis.

The similarity between Mars 2020 and MSL enabled Mars 2020 to reuse much of the MSL System Testbed infrastructure. The Mars 2020 System Testbed team reused and adapted the existing MSTB and FSWTB. However, the Mars 2020 System Testbed was unable to use the MSL VSTB for its mission needs. MSL’s own project needs and the cost required to adequately modify the system prevented the MSL VSTB's repurposing as the Mars 2020 VSTB.

After nearly a decade on the Red Planet, MSL's Curiosity rover continues to productively explore Mars. So long as Curiosity is operational, the MSL Project will need a System Testbed to support the four System Testbed functions. The MSL VSTB is the only remaining dedicated MSL System Testbed and is vital to the MSL Project’s continued success. MSL's need to maintain their own VSTB precluded Mars 2020 from repurposing the MSL VSTB for Mars 2020. Because of this, the Mars 2020 project decided it was necessary to build its own VSTB.

Had MSL's VSTB been available for Mars 2020, however, the technical hurdles still would have prevented Mars 2020 from reusing MSL's VSTB. Compared to the MSTB and FSWTB, the effort to convert MSL's VSTB to work for Mars 2020 would be too great. To make the MSTB and FSWTB compatible with Mars 2020, the Mars 2020 System Testbed Team modified the cabling, updated software and firmware, and integrated the new Mars 2020 hardware. The accessibility inherent in the stationary Systems Testbed enabled this. Though Mars 2020 shares many of the same design features as MSL, the rover stage design changed the

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most between the two missions. Converting MSL's VSTB from the MSL rover design to the Mars 2020 rover design presented the biggest hurdles. Relative to the MSL rover, the Mars 2020 rover design includes a new suite of instruments, an additional image processing computer, and a new sampling system. The mechanical and electrical interfaces of Mars 2020's instrument internal electronics differ from MSL's instrument internal electronics interfaces. To make room for the larger Mars 2020 sampling system, the Mars 2020 rover design effectively reduces the length of the Mars 2020 RAMP relative to MSL's RAMP. The Mars 2020 RAMP incorporates the added imaging computer where MSL had none. These changes ripple into changes in the RAMP mounting locations and harnessing design. The sum of these changes meant the effort to reconfigure the MSL VSTB to match the Mars 2020 flight rover design was too great.

2. BUILD TIMELINE

The VSTB buildup consists of four phases: preparation, the RAMP-Only Build, the Mobility-Only Build, and the Full Build.

Preparation began Fall 2018. Initial work focused on the VSTB build flow, schedule, and procuring the long lead items. Over the summer of 2019 the VSTB team was devoted to procedure development. Because the VSTB is a copy of the Perseverance rover, many of the flight build integration procedures could be used to build the VSTB, with only minor changes needed. As 2019 came to a close the VSTB team started to take delivery of the VSTB hardware. In December 2019 the team received the Simulation and Support Equipment and Ground Support Equipment. The Surrogate RAMP, a duplicate RAMP used for the first-stage build, was delivered in January 2020. These essential pieces allowed the VSTB team to set up the RAMP-Only Build test area.

In early March 2020 the VSTB team was waiting for delivery of the Rover Power Assembly (RPA) that conditions power to the rover, the internal power harness, and the internal command and data handling harness. The VSTB team received the internal power harness on March 16, clearing the way for preliminary electrical checkouts and hardware integrations. One day later, in response to the COVID-19 pandemic the Jet Propulsion Laboratory instituted mandatory telework. As a result, the VSTB team immediately suspended work. Due to the VSTB's importance to the Mars 2020 Project, VSTB work was provisioned to continue on March 23 once appropriate COVID-19 safety protocols had been reviewed and put into place. Initially, work continued with only one person on site at a time. This forced the VSTB team to learn quickly how to run a "safe-to-mate," normally a two-person operation, with one person on site and one person working remotely. The following week the JPL COVID-19 protocols allowed for two people to work on site together with appropriate PPE and precautions. The command and data handling harness and the RPA were delivered in late March. With all the necessary components in-hand, the VSTB team began electrically integrating the internals for the RAMP-Only Build.

The RAMP-Only Build used the Surrogate RAMP to electrically integrate the internal electronics and harnessing prior to mechanically integrating them onto the actual rover chassis. Recall that the RAMP, or Rover Avionics Mounting Plate, is the mounting interface for the internal electronics. The RAMP is enclosed by the rest of the rover chassis, which hinders access to the electronics and harnessing when mechanically integrated. Once the electronics and harnessing are installed within the rover chassis, portions of the harnessing must be removed in order to access the electronics. The Surrogate RAMP, without the rest of the chassis, gave the Mars 2020 System Testbed team access to the internal electronics throughout this stage of the build.

The Surrogate RAMP allowed the VSTB Team to integrate the internal electronics as needed. The greater access allowed for instrument hardware to be shared between the VSTB and the other System Testbeds. The VSTB team would borrow an instrument electronics box from one of the other System Testbeds to temporarily integrate it onto the VSTB. The Surrogate RAMP side access allowed the VSTB Mechanical Team to slide the box under the harnessing and mount it to the surrogate RAMP. The VSTB electrical team ran the electrical integration procedure to mate the box to the harnessing and do a functional test. Then the VSTB mechanical team physically removed the electronics box from the Surrogate RAMP and returned the box to the System Testbed that it was borrowed from. This limited the time the instrument team would lose access to testing their instrument in the other System Testbeds. Had the rover chassis been used, all instruments would have been mechanically integrated at the beginning, resulting in every instrument electronics box being off limits for V&V until all VSTB integrations were completed. As such, the Surrogate RAMP enabled the System Testbed Team to utilize the scarce subsystem resources more efficiently.

In addition to the efficiencies gained by sharing instruments, the Surrogate RAMP enabled efficiencies in redundant hardware use. Many of the rover internal electronics are redundant. For a given box, the primary box is called the A-side and the backup box is the B-side. Only one unit of each type of box is needed to operate the rover. The backups are in the design to replace the primaries in the event the primary fails. When only one unit of a box is integrated, this said to be a "single string" configuration. When both boxes are integrated, this is a "dual string" configuration. For the RAMP-Only build, the VSTB team had only one of each box available. The Surrogate RAMP's access relative to the rover chassis provided the flexibility to integrate each box first in its A-side configuration and then again in the B-side configuration.

The VSTB Team completed the RAMP-Only Build in mid-June 2020. While the VSTB electrical team focused on the

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Surrogate RAMP electrical integrations, the VSTB mechanical team prepared the VSTB rover chassis for the Mobility-Only Build. The Mobility-Only configuration includes the single-string avionics, a subset of instruments, the image processing computer, the Mobility subsystem, Rover Sensing Mast (RSM), High Gain Antenna (HGA), and Mars Helicopter Deploy System (MHDS). This pared down configuration includes the components that are needed to test the Mobility subsystem, along with any additional components that need to be tested during that phase. The remaining science instruments and the Sample Caching Subsystem (SCS) remained with the other System Testbeds. This separation of rover components allowed for parallel testing of Surface Sampling Operations and Mobility on separate System Testbeds.

The VSTB mechanical team started the Mobility-Only Build by integrating a thermal cooling system and internal electronics into the rover chassis. The VSTB harnessing team followed by laying out and connecting the internal harnessing. The electrical integrations performed in the RAMP-Only Build did not need to be repeated. After the VSTB internals were connected, the VSTB electrical team ran the Copper Path Test, which is a procedure that powers on the VSTB and each internal electronic box. This test verifies the internal electronics are connected and functioning. At the conclusion of the Copper Path Test, the VSTB mechanical team installed the belly pan, which sealed off the internals.

Once the VSTB team completed installing the internals, the focus turned to adding the external electronics. In the Mobility-Only Build this stage included mechanically and electrically integrating the RSM, HGA, the Mobility subsystem, the MHDS, the engineering cameras, the two Mastcam-Z cameras, and the RIMFAX antenna. The VSTB harnessing team installed the external harnessing, which connects the internal electronics to the external electronics. The mechanical team mounted each of the components to the chassis, and the electrical team performed the electrical integrations. Each of these integrations culminated in a functional test. The VSTB Team took images with each of the cameras, performed a sounding with the RIMFAX Antenna, and "wiggled" each mechanism. The mechanism wiggle tests verified the mechanism was connected to the motor controller, the motor controller properly controlled the mechanisms, and the mechanism moved in the commanded direction.

On September 1, 2020, the VSTB team drove the rover on flat ground for the first time. This was the final milestone prior to moving the VSTB to the Mars Yard. Demonstrating drive functionality is crucial prior to moving, as the tractor used to transport the VSTB between buildings does not have the clearance to move the rover into the Mars Yard Garage directly. At the conclusion of the first drive, the VSTB was ready for its move to the Mars Yard Garage.

The move came on September 5, 2020. After the VSTB electrical team moved the electrical ground support equipment to the Mars Yard Garage, the VSTB mechanical team used a tractor with a crane to carry the VSTB to the garage entrance (Figure 1), where it was lowered to the ground just outside the garage door. The VSTB electrical team connected the VSTB umbilical, powered on the VSTB, and commanded the rover to drive forward into the Mars Yard Garage. The VSTB was then ready to perform mobility verification and validation.

Figure 1 The VSTB Being Carried by Tractor to the Mars Yard Garage

The Full-Build VSTB is the final VSTB configuration. In addition to the hardware installed in the Mobility-Only Build, the Full-Build adds the backup computer, all remaining instruments, and the Sample Caching Subsystem (SCS), which includes the Robotic Arm (RA), Corer, and Adaptive Caching Assembly (ACA). While adding a few extra components may sound simple, it requires a complex series of operations that include moving the VSTB out of the Mars Yard to another building for maintenance, flipping the rover, opening it up, then removing the electrical harnessing and certain electrical components to clear the way for installation of internal cabling and instruments not previously integrated onto the rover. In many ways, it requires re-building the rover from the RAMP up. This final configuration is the most flight-like rover the Mars 2020 System Testbed will have.

3. Electrical Integration Procedures

Throughout all build phases of the rover, many electrical components are integrated that receive and distribute power and data to other components on the rover. All electrical signals coming in and out of newly integrated components must be properly checked prior to mating and powering on.

Ensuring the Electrons Play Nice

The main responsibility of a System Testbed engineer is to sufficiently understand the electrical signals associated with

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each component such that they can ensure everything has been properly tested prior to integration and operation. The testbed must be assembled from all of its parts, each of which is complex, sensitive, and often very valuable. It is extremely important that each component is treated with care and integrated with the rest of the testbed methodically and deliberately.

Once a new component is brought physically into the venue and securely mounted to a workbench, it must be ensured it is ready to be electrically connected to the power and data interfaces that control its operation. There is risk associated with integrating electrical signals, and a set of procedures is implemented to buy down that risk. Each box generally has multiple electrical connectors for these interfaces, and each connector contains anywhere from nine to a hundred signal paths.

These measured signal paths must match up with the designed signal paths in the cabling with which it interfaces, which also must match the intended signal paths in the devices on the other end of the cabling. Once it has been determined that the signal paths and properties are appropriate, it is referred to as being "safe to mate." The method by which it is determined whether a connector is safe to mate is through an Electrical Integration Procedure (EIP).

In writing an EIP, testbed engineers work with the cognizant engineers of the individual devices to develop a road map for the order and particulars of each connector prior to mating them. The standard EIP has three main sections: power-off measurements, power-on measurements, and functional testing, with each section assessing a higher level of risk and achieving more intensive interactions with the new device.

Power-off measurements: While the new device is electrically disconnected from the rest of the system, each pin of each connector is individually measured for electrical resistance to chassis ground using a digital multimeter. Resistance of each circuit pin pair is also measured during this process. The results of these measurements are compared to predicted values provided by cognizant engineers from each side of the interface. Any discrepancies are investigated and properly dispositioned prior to moving forward with the rest of the procedure.

Power-on measurements: The system power is turned on and another set of measurement are taken for voltage with respect to chassis ground, as well as voltage on applicable circuit pin pairs. Subsequent steps are generally specific to the device being integrated, but entail a process by which circuits are verified as safe to mate based on the measured signals while system power is on.

Functional testing: Once all the circuits have been connected between the device and the rest of the system, the system's on-board software is used to communicate with the new device via its data interfaces. An oscilloscope is typically used to watch the data transmissions between the devices to assess bitrates and signal fidelity. If all is well, the device is considered safe to direct-mate, and after a final basic functional test the EIP process is considered complete.

OUR BEST FRIEND BOB

Testing every pin on the entirety of the rover's hundreds of connectors is a daunting task, and the connectors are generally quite small such that they fit within the volume and mass requirements of the mission. As a result, it would be tedious and challenging to physically probe each of these individual pins. Enter the break-out box.

The break-out box, or BOB, and the associated BOB cables, are two of the most important tools in the testbed engineer's toolbelt. The standard BOB consists of a metal shielded enclosure with two 61-socket D38999 circular connectors on one side, and 61 pairs of red and black banana-style receptacles on the top. BOB cables have the mating 61-pin connector on one end, and one of a seemingly infinite variety of connector types on the other end. Using a database and organized filing system, the testbed facility has a collection of dozens of different BOB cables available to connect to almost any connector type that is required for all the EIPs to be completed. Once the BOB is connected to a device under test via a BOB cable, a user has easy access to each pin on that connector for performing EIP measurements using a digital multimeter or oscilloscope (Figure 2).

Figure 2 BOB Setup During an EIP. Shorting Bars Patching Red and Black Side Pins Are Shown, and a Digital Multimeter is Shown Probing Pin Signals.

There are two 61-contact connectors on a BOB so that one side can be connected to the device under test, and the other side can be connected to the mating connector on the existing system's side. By convention, the device under test is referred to as the "red-side" and the existing system is referred to as the "black-side", referring to the red and black banana connectors on the top of the BOB. This system makes it trivial to connect red-side to black-side in the applicable step of the EIP using a simple shorting bar between the two

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adjacent banana receptacles (see Figure 2). It also allows connection between pins on the same side, or connecting additional test equipment for troubleshooting purposes. When power is first connected between the red and black sides, it is most common to use a regular banana patch wire. This allows the use of a current probe on that patch wire, which when viewed on an oscilloscope, provides a characteristic current in-rush curve that can be used for troubleshooting or can be referenced in subsequent EIPs of the same or similar devices.

A New Challenge, a New Philosophy, and the Just In-Time Tool

Even with the added benefit of the break-out box and BOB cables, it still takes quite a bit of time and effort to take, report, and record measurements on hundreds of pins across multiple connectors. It is at least a two-person job to execute a traditional EIP. Typically, one engineer follows the procedure, prompting the other engineer to take the specified measurements, then manually records those measured results. This process can be tedious, tiring, and prone to human error, especially when many measurements in a row are an identical value such as less than "zero point two ohms" to indicate a short circuit, or "O-L" in the case of an open circuit. It is also fairly common for a resulting measurement not to match the predicted value; in which case the procedure is generally put on hold for at least a few minutes to investigate and disposition.

With all this in mind, the Mars 2020 VSTB team found themselves in an interesting situation when JPL essentially closed its doors to protect its workers from the COVID-19 outbreak. After shutting down and assessing the personnel needs of mission-critical tasks, VSTB team members were permitted to return to lab and work alone to perform tasks that are normally performed by a two-person team. The team showed resilience in its ability to adapt to the situation by pairing the in-person engineer with remote support, ensuring the project could continue moving forward.

Conveniently, the team had already begun designing a tool referred to as the AutoBOB, a computer-controlled system for quickly taking dozens of measurements and comparing them to predicted values in a fraction of the time normally required for the two-person team. The AutoBOB was quickly recognized as an invaluable tool given the new circumstances, as it could be operated by anyone with access to the local area network, including the remote participants on the VSTB team. The AutoBOB consisted of an off-the-shelf benchtop digital multimeter data acquisition (DAQ) unit with three multiplexer relay accessory cards installed, and a custom-built break-out box interface cable using the standard 61-pin connectors. This interface cable was built as a Y-splitter cable, so the AutoBOB would be connected in-between the device under test and a traditional break-out box. This allowed the in-person engineer to manually take measurements as needed if the AutoBOB read a value incorrectly or was otherwise having technical issues.

To operate the DAQ and make it the automated tool it was intended to be, a script was also developed to provide input to the DAQ on the quantity and type of the measurements to take in bulk. The script could be configured entirely from command line arguments, or by specifying a pre-made measurement file that included predicted measurements. The script would take the inputs, develop a test sequence and send it to the DAQ, which would take the measurements and return the results. The script would take the results, compare them to the predictions, save the "as-run" results to a file, and display them for the user.

On March 25 2020, the AutoBOB was used for the first time in-person in the context of an official EIP. Soon after, the VSTB team was permitted to have two engineers working together in-person. While having more engineers on-site may have diminished the need for the AutoBOB, the team recognized its potential. Since other projects were put on hold due to the pandemic, there was increased availability of remote engineers. The VSTB team capitalized on the increased personnel availability by staffing shifts with two in-person engineers and one remote engineer. The remote engineer walked through the procedure, maintained a log of the shift in the activity report, and operated the AutoBOB. This arrangement freed up the two in-person engineers to concentrate on hardware reconfiguration and carry out the new COVID cleaning protocols. This plan proved to be an incredibly efficient use of resources and resulted in the completion of EIPs in record time.

4. Mechanisms

The EIP process can be long and tenuous, but is critical to the successful integration of the rover system. The practice of verifying all electrical signals on the VSTB ensures that the intricate system of components will operate safely and as intended. On the M2020 rover, a complex array of state-of-the-art science instruments and mechanisms must work together in order to meet the mission objectives. Once these instruments and mechanisms have been electrically integrated onto the VSTB, they are ready for testing and use.

While the rover's science instruments deservedly generate much attention for their ability to collect mission critical data, proper mechanism functionality is likewise an indispensable element required to meet mission objectives. Mechanisms are essential to the rover's basic operations, from driving on the Martian surface, directing the RSM for imaging and science operations, and positioning the HGA to communicate with Earth; as well as more intricate and complex tasks associated with the collection and caching of soil and rock samples. To support mechanism actuation, Perseverance relies on a total of thirty-three actuators composed of seven different types of 3-phase DC brushless motors with varying accuracy and power (Walker, 2015). Most motors possess a gearbox, a brake, and sensors for commutation, depending on the application. In applications where absolute position sensing is needed, the Hall effect sensors are supplemented with

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resolvers on the mechanism's actuator gearbox output. Additionally, contact switches (CSW) and force sensors are used on the SCS mechanisms, which include the ACA, Corer, and RA. The control of these actuators and reading of the actuator sensors (CSWs, force sensors, resolvers, and encoders) is achieved by the Rover Motor Controller Assembly (RMCA).

The RMCA is composed of eighteen separate boards, each serving a particular purpose, with some of them providing redundancy. The functions that the individual boards provide include power conversion and distribution, motor control processing, serial communication, actuator sensor reading, motor control drivers, and brake control. Certain boards are capable of collecting telemetry from the motor hardware and subsequently relaying that information to the appropriate processing card. Compared to a commercial controller, Perseverance's RMCA architecture is highly customized. It operates on software developed in-house, which utilizes over a thousand actuator tuning parameters. Moreover, the RMCA is built with space-rated hardware using in-house flight specs.

A critical purpose of the VSTB is to ensure proper mechanism functionality. With the RMCA's powerful capability of controlling the rover's mechanisms, the VSTB offers the highest fidelity testbed available to test the interaction between the flight software, the motor controller software, and the mechanism hardware.

5. How is the VSTB Used?

The VSTB operates in the Mars Yard at JPL, a simulated Martian landscape used by both the MSL and Mars 2020 VSTB rovers. The Mars Yard features a rocky hill where the rovers can drive up and orient the chassis at various degrees of tilt. This is similar to the testing done on the FSWTB Hexapod, but the VSTB has the full kinematics of the entire rover system.

There are a few reasons why having a Perseverance twin is beneficial to the project. The VSTB allows us to train the operations team to handle anomalies prior to landing, dry-run and prepare for first time activities with flight-like kinematics, and aid in anomaly investigation with real hardware.

How The VSTB Is Different From Perseverance

Testing a system that is not designed to operate on Earth has a number of challenges. To address the different operational environments, a few deviations exist between the VSTB and Perseverance:

- Not all the rover PRTs are installed on the VSTB
- Certain heater circuits, intended to protect hardware from the frigid Martian environment, are not included on the VSTB
- Umbilical cabling is used instead of the RTG and radio communications
- A gaseous nitrogen cooling system is integrated onto the VSTB to enable operation during hot Pasadena summers
- Fuses are used to protect the batteries from unintended power supply surges.

First Time Activities: Moving through Mission Phases

The testbeds are designed to mimic the flight system such that the data received by the operations team will resemble the data coming from Mars. The high fidelity of the VSTB makes it a valuable training ground and validation tool to dry-run first time activities (FTAs) planned for Mars. FTA tests are developed with specific criteria that match the Mars 2020 mission goals. These system tests usually involve interactions between multiple subsystem operations teams, commanding the rover exactly as planned in flight. Usually, commands are sent in sequenced lists that are executed autonomously. These sequences are built in preparation for the system test, and will eventually be used for commanding the rover. Every major milestone that is performed on Mars is always first executed using the System Testbeds. Examples of this practice include the rover's first drive, or the Mars Helicopter drop. After completion of the Full Build, the VSTB possesses all system instruments and is the venue where all FTAs are completed.

ORTs

Operational Readiness Tests (ORTs) are unique in that the unit under test is the personnel, rather than the hardware. Some ORTs are designed specifically to train the operations teams through potential flight anomalies, while other system tests involve dry-running an FTA, as described above. ORTs may involve system fault-injections to expose the operations teams to off-nominal scenarios where an anomaly occurs during flight. Because System Testbeds are built to mimic the flight system, the data received from the operations facility will appear as flight data. The ORT trains the operations team through various processes, from monitoring the spacecraft, sending commands, and most notably, anomaly investigations.

Anomaly Investigation

Almost a decade's worth of effort was used to verify Flight Software (FSW) and instrument capabilities before launching Perseverance to Mars, but the project needs to be prepared for certain system-level interactions to change once Perseverance is on another planet. When an issue occurs during flight, the operations teams rely on the VSTB to replicate the behavior, develop a workaround, and/or test a fix. Since the VSTB is built with sufficient hardware to mimic the flight vehicle, the testbed can be used to shadow the rover as it drives around on Mars. This feature is particularly useful during the major milestone events like the first drive or first coring activity.

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Given the number of instruments operating across multiple sols (Martian days) there's no telling what kind of behavior might be encountered with the wide variety of unpredictable system interactions that may occur. One such example of a flight anomaly was the "watchdog" timer issue within the Ingenuity Mars Helicopter flight software. On the sols leading up to the helicopter's first flight, as the rotorcraft was testing its first rotor spin, a software-based timer prematurely interrupted the sequence that was controlling the transition from "preflight" to "flight" mode (Grip, 2021). The issue required an update to the helicopter flight software, which was tested in the VSTB prior to executing the sequence on Mars. Shortly after updating the watchdog timer, the rotorcraft successfully demonstrated its ability to fly on another planet.

SUBSYSTEM TESTING

Sample Caching Subsystem (SCS): The rover SCS features a Robotic Arm (RA) with a coring drill meant to collect samples within the Adaptive Caching Assembly (ACA). Once installed on the VSTB, the SCS Team is able to utilize both the Mobility subsystem and RA as an end-to-end test for a science mission. The team is able to drive on different types of terrain and drill on selected samples at various degrees of tilt. As an example, prior to the VSTB, drilling operations were not able to be performed outside of the Hexapod, which can only tilt a fixed chassis. Engineers had not validated the ability of the rover to apply enough force to actually drill through the sample while on a slope. Careful observation was taken in preparation for drilling since the RA would apply a force of 50N on top of the specimen prior to taking its first sample. With that much force applied at a tilt, there was concern that slip could occur from its initial position. This is the type of testing that only the VSTB can provide. The Mars Yard possesses slopes of varying magnitudes and surface terrain which provides SCS engineers with variability in the types of drilling operations that can be used to validate this type of operation.

Mobility: Having a full-size vehicle allows for full testing of the upgraded Mobility system. Compared to Curiosity, Perseverance possesses an extended and heavier chassis, redesigned wheels, and a new Auto Navigation (AutoNav) functionality implemented into the FSW (Rieber, 2018). These new capabilities have to be fully tested on the VSTB before the first drive on Mars.

Mobility V&V occurred in a number of phases, and using an array of testbed venues. Certain activities were able to be achieved using lower fidelity tests, however much of the final validation had to take place using the VSTB as the highest fidelity system available. In general, there are 3 criteria used to assess the fidelity of a testbed:

1. Hardware Fidelity
2. Avionic System (AVS) and FSW Fidelity
3. Environmental Fidelity.

The fidelity of the various testbed venues is displayed in Figure 3. The lowest fidelity venue, in most respects, is the Workstation Testset (WSTS), which is a simulation environment where FSW is exercised against only software simulations of hardware.

As an intermediate testing platform, the Mobility team utilized the "Scarecrow" test rover, which gets its name from its minimal level of "brainpower," i.e., AVS fidelity. While the Scarecrow rover possesses none of the instruments or key avionics aboard the flight rover, its lighter chassis actually provides notable benefit to the Mobility team in that its weight more closely matches that of Perseverance in Mars' gravity, being approximately 3/8 that of Earth. As a result, certain terrain performance verification activities may be at least partially tested on this venue. Scarecrow was also essential in the wheel redesign effort, where longevity and resilience of the wheel design was tested over various terrains (Inotsume, 2019). Without sufficient fidelity in its avionics capabilities, instrumentation, and weight distribution, Scarecrow falls short as an adequate venue for achieving full verification and validation of mission requirements.

While the flight vehicle possesses the highest possible level of hardware and AVS/FSW fidelity, limitations on the scope of flight qualification testing necessitate the existence of the VSTB as the highest fidelity testbed in all 3 metrics. That is, only the VSTB can be put through the necessary paces to provide sufficient testing of verification items in the flight-like environment from a Mobility subsystem perspective, i.e., in JPL's Mars Yard. As discussed previously, the VSTB system-level build occurred in two phases, beginning with the Mobility-Only Build. This initial build could achieve very high fidelity in all metrics other than hardware not critical to the testing of the Mobility subsystem specifically. Following the Full Build, the VSTB is able to achieve the highest possible level of system fidelity.

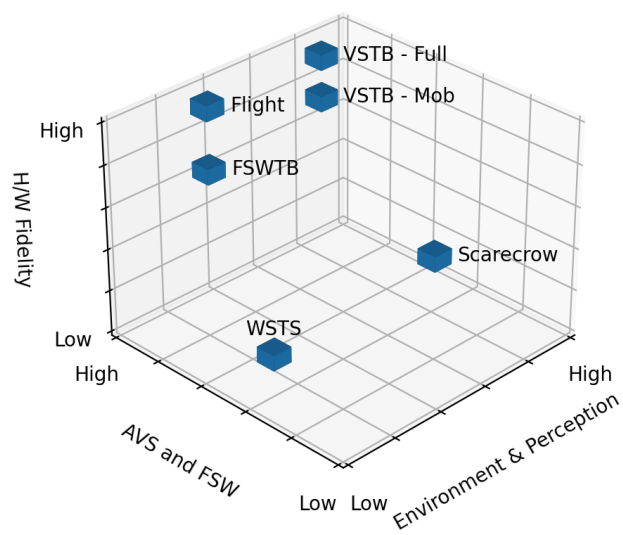

Figure 3 Testbed Venue Fidelity

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The Mobility V&V activities were initiated for certain verification items that could be at least partially verified using WSTS. The FSWTB was also used to perform a number of verification activities not requiring a high-fidelity system, including the testing of parameters, command logic, and fundamental software-based Mobility functionality such as mapping. Upon completion of the VSTB Mobility build in Fall 2020, the majority of the Mobility V&V campaign could be performed in the JPL Mars Yard. The early phase of the Mobility surface, guidance, navigation, and control (SGNC) V&V campaign involved primarily low-level commanding, which tested the functionality of visual odometry (VO) capabilities. VO is used by the rover to calculate its distance traveled by using FSW to compare images taken by the NavCams at successive positions. When the VO results are compared to the recorded number of wheel revolutions that occurred between the positions, the wheel slip may also be determined.

Subsequent phases of SGNC V&V centered on behavior testing, most notable that of AutoNav functionality which enables Perseverance to travel significantly greater distances in a much shorter time compared to its predecessor. Additionally, scenario testing was designed to simulate various circumstances such as multi-sol drives, and precision approaches toward potential hazards.

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Leadership of the VSTB team has changed through the phases of the project. From project planning through the Mobility-Only build, Matthew Stumbo served as Systems Lead, with Jose Trujillo Rojas as Mechanisms Lead, and Justin Foley as Avionics Lead. Jose Trujillo Rojas took over leadership of the VSTB in September 2020 for the Full Build. At the time of the writing of this paper, Jose continues to lead the VSTB team, Christopher Matthes serves as Electrical Lead, and Terence Dang is the Mars 2020 Testbed Lead.

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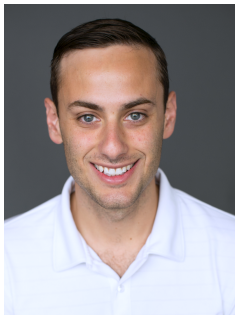
BIOGRAPHY



Christopher S. R. Matthes *received a Ph.D. in Aerospace Engineering from UCLA in 2016. He also has a M.S. from UCLA and a B.S. from Michigan State University, both in Mechanical Engineering. His thesis focused on characterizing material surface evolution in electric propulsion devices. Dr. Matthes began his career as a systems engineer working in thermal energy applications and systems at NASA Jet Propulsion Laboratory, focusing on radioisotope power systems. He served as the Project Systems Engineer for the enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG) Project, which aimed to upgrade the existing MMRTG system with improved thermoelectric materials for better efficiency and performance. More recently, he has moved to the Mars 2020 Project to work as a system testbed engineer. During his time in the testbed group, he has been heavily involved in the building of the Vehicle System Testbed (VSTB) for the Mars 2020 rover, and using it for verification and validation testing in JPL's Mars Yard. He also holds lecturer positions at UCLA and Pasadena City College, where he teaches engineering laboratory courses.*

Matthew T. Stumbo *received a M.S. in Electrical Engineering from USC in 2018 and a B.S. in Aerospace Engineering from Cal Poly San Luis Obispo in 2013. Matt began his career as a systems engineer working on the Mars Science Laboratory (MSL) System Testbed Team at NASA Jet Propulsion Laboratory. On MSL's System Testbed Team he gained experience operating and maintaining MSL's VSTB. He then joined the MSL Engineering Operations team to support daily operations of the Curiosity rover on Mars. Matt moved on from MSL to join the Mars 2020 System Testbed Team in 2016 where he focused on system testbed infrastructure, avionics, and power. Matt led the Vehicle System Testbed (VSTB) Team as the VSTB Systems Lead from the start through the Mobility-Only Build. Following Perseverance's landing on Mars, Matt left the M2020 System Testbed Team to work on the Europa Clipper Assembly, Test, and Launch Operations Team.*

Justin Foley *started his aerospace career working in the CubeSat laboratory at the California Polytechnic State University in San Luis Obispo where he also obtained his B.S. in Physics and M.S. in Aerospace Engineering. During his time there as a student he gained experience designing, building, testing, launching, and operating small spacecraft. After graduation, he continued to work with Cal Poly as a contractor for NASA and the National Reconnaissance Office, serving as a secondary payload integration engineer tasked with preparing and launching satellites built by US universities and other organizations from around the world. Justin left his work with CubeSats to join the Mars 2020 System Testbed Engineering team at JPL where he worked in nearly every subsystem area, culminating with a stint as the avionics lead for the first build of the Vehicle System Testbed (VSTB) before transitioning to act as the testbed lead for entry, descent, & landing (EDL). After landing, Justin continued to oversee the Mars 2020 testbeds until transitioning to work on the Mission to Psyche's Assembly, Test, & Launch Operations team.*

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Terence Dang *received a B.S. in Electrical Engineering from UC Irvine in 2010. Terence joined the testbed team in 2019 with prior experience with systems integration and validation from commercial aircrafts, as well as electrical circuit analysis in satellite power systems. Since joining the testbed team he served as the Avionics Lead for the Vehicle System Testbed (VSTB) Team during the Mobility-Only build. Terence currently leads the Mars 2020 Testbed Team while the program continues its Operations phase on the surface of Mars.*

Jose G. Trujillo Rojas *has a B.S. in Aerospace Engineering and a B.A. in Physics from California State University, Long Beach; and is currently pursuing a M.S. in Astronautical Engineering at University of Southern California. Before his aerospace career, Jose enlisted in the United States Marine Corps where he sharpened his leadership and project management skills serving as a non-commissioned officer. Upon completion of his military service, Jose enrolled in the United Association Veterans in Piping (VIP) Program, where he trained and worked as a fabricator and welder for the union. In pursuit of a career in aerospace, Jose subsequently enrolled at CSULB as the first in his family to attend college. While in school, he interned with the Boeing company where he was awarded two Boeing patents for developing Variable Sealant Flow End Effectors. In 2016, Jose joined NASA Jet Propulsion Laboratory as a system testbed engineer. During his tenure with the testbed team, he led the development of the FSWTB sandbox (mechanism lab space) infrastructure and served as the Mechanism Lead for the Vehicle System Testbed (VSTB) team during the Mobility-Only build. Jose is currently the M2020 Testbed Deputy Lead and the VSTB team lead.*

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