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List of Acronyms

1. AMO…Advanced Manufacturing Office
2. CAFE…Corporate Average Fuel Economy
3. C'Bore…Counterbore
4. DOE…Department of Energy
5. EDM…Electro-Discharge Machining
6. ETDE…Energy Technology Data Exchange
7. FOA…Funding Opportunity Announcement
8. GDi…Gasoline Direct Injection
9. HLTP…Hybrid Laser Tube Processing
10. HP…High Performance
11. HSK…Hohl Shaft Kegel (German→English translation: hollow-shank taper)
12. ID…Inner (Inside) Diameter
13. INIS…Informational Nuclear Information System
14. MAxHP…Multi-Axis Hybrid Processing
15. ML-5…5-Axis, Femtosecond Laser Machining Center
16. mMTs…Micro/Mesoscale Machine Tools
17. OD…Outer (Outside) Diameter
18. ORNL…Oak Ridge National Laboratory
19. SLS…Shared Laser Source
20. SS…Stainless Steel
21. TRL…Technical Readiness Level
22. US…United States

1. Executive Summary

Machining methods across many industries generally require multiple operations to machine and process advanced materials, features with micron precision, and complex shapes. The resulting multiple machining platforms can significantly affect manufacturing cycle time and the precision of the final parts, with a resultant increase in cost and energy consumption. Ultrafast lasers represent a transformative and disruptive technology that removes material with micron precision and in a single step manufacturing process. Such precision results from athermal ablation without modification or damage to the remaining material which is the key differentiator between ultrafast laser technologies and traditional laser technologies or mechanical processes. Athermal ablation without modification or damage to the material eliminates post-processing or multiple manufacturing steps. Combined with the appropriate technology to control the motion of the work piece, ultrafast lasers are excellent candidates to provide breakthrough machining capability for difficult-to-machine materials.

An expert team of industrial partners was assembled for this project. Delphi Automotive Systems, LLC (Rochester, NY), as the overall project lead, is a Tier 1 automotive supplier with expert design and manufacturing capabilities for a broad range of components, including fuel injectors. Raydiance, Inc. (Petaluma, CA) was the industry leader in the production and application of ultrafast, commercial grade laser systems until Coherent, Inc. purchased the assets of Raydiance in July 2015. Microlution, Inc. (Chicago, IL) offers critical expertise in custom micromachining platform design and multi-axis motion control.

At the project onset in early 2012, the project team recognized that substantial effort was necessary to improve the application of ultrafast laser and precise motion control technologies (for micromachining difficult-to-machine materials) to further the aggregate throughput and yield improvements over conventional machining methods. The project described in this report advanced these leading-edge technologies thru the development and verification of two platforms: a hybrid enhanced laser chassis and a multi-application testbed.

The hybrid enhanced laser chassis uses ultrafast laser drilling along with high-speed milling to produce fuel injector metering orifices for gasoline direct injection (GDi) fuel injectors within the automotive industry. Combining these operations on a single chassis offers a fast, high precision manufacturing method that provides substantial reduction in cycle time and energy consumption compared to the baseline method of electro-discharge machining (EDM). Global mandates are being implemented for substantial improvements in fuel economy and reduced CO_2 emissions. For example, the US passenger car fleet in 2016 must show a 42% increase in corporate average fuel economy (CAFE) compared to requirements mandated in 2010. Further legislation is nearly finalized for future years demanding CAFE in 2025 be improved by roughly 120% compared to the 2010 baseline. In response, vehicle manufacturers are implementing a variety of technologies to reduce friction and drag, decrease mass, and improve the efficiency of the powertrain. GDi engines are one technology seeing broad application. These engines enable increased engine compression ratio and/or better compatibility with turbocharging to offer substantial engine efficiency improvements during typical driving. Turbocharged GDi engines can be downsized to improve fuel economy by 10% or more without any sacrifice in vehicle performance or drivability. However, fuel delivery directly into the cylinder substantially increases the spray generation and flow requirements of GDi fuel injectors compared to port fuel injectors. Meeting these requirements demands the design and manufacture of high precision components to tight tolerances with excellent part-to-part repeatability and the ability to survive more than a billion engine cycles. Delphi chose this specific, challenging application to allow evaluation of the prototype platform system against rigorous, real-world requirements aimed at significant global energy and CO_2 reduction. Parts produced as a result of this project meet Delphi's established performance targets and product quality characteristics.

The multi-application testbed uses the same advanced technology to demonstrate the ability to manufacture electronic and biomedical parts with new geometry made from new, hard-to-machine materials. This testbed offers a fast, high precision manufacturing method that eliminates costly process steps and substantially reduces energy consumption when processing hard-to-machine materials across a broad range of high-value markets (compared to other available processing methods). Raydiance (now Coherent) and Microlution have customers across a number of industries and the objectives of the project were designed to allow rapid implementation of these new materials and applications. Parts produced as a result of this project meet the performance targets and quality characteristics of Microlution's customers.

2. Introduction

This project was initiated in response to DE-FOA-0000560 Topic Area 1, Subtopic 1D: Sustainable Manufacturing. The focus area for this subtopic as described in the Funding Opportunity Announcement (FOA) is as follows:

> Technologies that enable the manufacture of materials or components with multiple market applications and new manufacturing technologies that reduce process steps, materials usage, or parts count, thereby reducing the embedded energy in the manufacturing value chain. Design and process tools for manufacturing process selection at the product conceptual stage to meet specific cost, time, energy intensity, and life cycle energy consumption requirements.

The manufacturing technology in this project is well aligned with the goals of this FOA. In addition to the specific application for the GDi fuel injector metering orifices critical to Delphi, the technologies developed in this project apply to a broad industrial base in areas such as medical device manufacturing, medical therapies, industrial laser processing, biosciences, and defense markets. The techniques developed reduce process steps, materials usage (consumable tools), and parts count (consumable tools) for producers. Finally, this project was driven by increased manufacturing complexity required to produce new fuel injectors necessary to meet upcoming emissions and fuel economy requirements. The enhanced laser chassis developed had clear cost and cycle time goals that had to be met in order to prove it viable for a production application.

The complementary expertise of the project partners was integrated to deliver the specific project objectives listed in Table 2.1.

Table 2.1: Specific Project Objectives

Objective 1	Develop processes which will best use the latest ultrafast laser technologies for efficient machining of difficult geometries in numerous materials.
Objective 2	Develop motion control hardware that integrates seamlessly with the laser control logic.
Objective 3	Provide conceptual design of production line systems which will take maximum advantage of the unique properties of ultrafast lasers as a machining tool and dramatically enhance factory throughput.
Objective 4	Develop and verify a prototype micromachining platform based on ultrafast laser technology to manufacture GDi fuel injector metering orifices. This high precision platform will reduce manufacturing cycle times and energy consumption compared to currently available processing methods.
Objective 5	Develop and verify a multi-application testbed based on ultrafast laser technology that can accommodate new materials, part geometries, and processing requirements for electronic and biomedical industrial applications. This manufacturing method will reduce process steps and energy consumption for hard-to-machine materials across multiple markets compared to currently available processing methods.

Objective 1 applied the proven benefits of ultrafast laser technology to develop new manufacturing processes for difficult-to-machine materials used in the many industrial applications where there is a clearly identified requirement for high precision, athermal micromachining. The industrial applications targeted included the fabrication of automotive and aerospace components, medical devices, solar cells, microelectronics, and mobile devices. Raydiance led the efforts for this objective while Delphi defined specific piece-cost and cycle time requirements to ensure completion of this objective offered a competitive machining process for the final prototype micromachining platform.

Objective 2 drove fundamental improvements to the motion control and measurement systems provided by Microlution coupled with efforts by Raydiance to ensure the appropriate integration of the laser. Delphi again dictated requirements for this objective to ensure relevance with the final prototype micromachining platform.

Objective 3 resulted from the combined efforts of Delphi and Microlution. This objective capitalized on the fundamental technology gains in Objectives 1 and 2 to design the fundamental layout of a prototype micromachining platform offering improvements in cost and cycle times.

Objective 4 was delivered by Delphi and Microlution. Microlution built a prototype micromachining platform (otherwise known as a hybrid enhanced laser chassis) for GDi fuel injector metering orifices and then Delphi deployed this prototype platform to build application-specific injector hardware which met rigorous performance requirements. This allowed for confirmation of the system design in a production-intent environment.

Objective 5 was delivered by Microlution. Microlution built a multi-application testbed to accommodate new materials, part geometries, and processing requirements for electronic and biomedical industrial applications. This proved that the technology initially developed for use in the automotive industry was also a viable manufacturing solution in other markets.

Overall, this comprehensive project developed the prototype micromachining platform from Technical Readiness Level (TRL) 4 to TRL 6 based on the technology research levels defined in the FOA. To ensure that the technology met real-world needs, the enhanced laser chassis was developed and verified for a specific, challenging application: micromachining of fuel metering orifices for GDi fuel injectors. Raydiance and Microlution advanced their existing ultrafast laser and precise positioning technologies to enable rapid machining of complex shapes. Delphi set the requirements and executed the specific application work to deploy these advanced technologies to machine the GDi fuel injector metering orifices. Injector hardware was built from the prototype platform and the spray and flow characteristics were evaluated using Delphi-standard metrics. The manufacturing technology developed was proven production-viable based on performance and cost.

Both platforms are fully compatible with the current and future domestic manufacturing infrastructure. There are no limitations based on platform size or footprint, and no unique power requirements to implement the manufacturing technique in a production environment.

All objectives were structured to ensure that the manufacturing process met key cycle time and cost requirements. Injector hardware was built from the enhanced laser chassis and the spray and flow characteristics were evaluated using Delphi-standard metrics to verify that the manufacturing technology was production-viable.

By utilizing ultrafast laser technology, energy productivity improvements are expected through a number of means and efficiencies. Overall, the developed technology is expected to increase energy efficiency over standard machining platforms by approximately 20-25%. Cycle time is expected to improve 18x over EDM, which will reduce both the number of EDM units requiring power as well as the materials and energy to manufacture those units. The replacement of high precision tooling (consumables) with a beam of light will reduce the energy required to produce and ship these consumable parts. Finally, athermal machining with improved precision will reduce rework and scrap rates, and eliminate secondary processes such as etching, surface cleaning, or deburring.

The expected energy efficiency improvement described offers a corresponding 20-25% decrease in CO_2 emissions due to energy consumption. Additionally, the ability to eliminate surface cleaning or etching processes (i.e. post processing) due to the high precision machining capabilities reduces the use of toxic chemicals such as acid baths.

The technology is expected to have a substantial benefit to the overall US manufacturing capabilities. Ultrafast laser manufacturing is an emerging field with aggressive investment by competitor nations including South Korea, France, and Germany. Recent advances in the technology have been expanding the capabilities and application of the tool. To fully realize the energy and economic benefits, the manner in which the energy is delivered may need to be modified and tailored for each material and application. Executing this project offered the important understanding of how to best apply an ultrafast laser in concert with an integrated part/motion control system. This knowledge will enable far more industries to develop previously unproducible designs, increase part quality, and maximize factory throughput.

Reduction of process time is a key benefit for the technology in the project. EDM is a standard method to machine metering orifices for fuel injectors, but has an inherently long cycle time. The manufacturing method is expected to reduce this cycle time by 18x.

The benefits described have been estimated based on the replacement of today‘s conventional technologies with an ultrafast laser micromachining platform assumed to meet all technical and cost objectives for the project. The industrial project partners have substantial manufacturing expertise that served as a good foundation for estimating the benefits.

3. Background

The primary objective of this project was to develop a versatile, high metal removal rate manufacturing system which enables the micromachining of complex shapes in difficult-to-machine materials. The development and commercialization of such a system has applications across various industries and provides US companies with a productivity "game changer" that results in a significant advantage over foreign competition and a dramatic reduction in energy usage per unit produced.

Both the hybrid enhanced laser chassis and multi-application testbed constructed as a result of this project were designed and built within the United States using a combination of "state-of-the-art" elements, with an ultrafast laser being the metal removal technology. Ultrafast lasers are effective for ablating a wide range of materials with micron level accuracy without imparting heat to the target. As such, it was deemed the preferred candidate technology to micromachine more complex shapes. Complementary technologies were provided by Raydiance and Microlution during the development of the system in order to meet the stringent machining requirements of the GDi fuel injector metering orifices as well as some hard-to-machine components within the electronic and biomedical industries.

Traditional manufacturing platforms are poorly suited to produce small parts with high accuracy requirements. Such pieces are traditionally manufactured on platforms that are too large, too inaccurate, and too inflexible to deal with today's challenges. Traditional machine tool manufacturers take an incremental approach to building more precision and performance into their products resulting in equipment that is larger, more expensive, and more complex. Conventional manufacturing processes offer only tradeoffs instead of a clear competitive advantage. Current technology options for micromachining through-holes for example are limited to drilling, EDM, or stamping (piercing). Table 3.1 outlines the advantages and disadvantages of traditional techniques for two common geometries: cylindrical holes and blind holes or counterbores. As noted, conventional drilling, stamping, and milling have a cycle time advantage over EDM, but leave either hanging burrs or pucker that require post processing to remove.

Table 3.1: Traditional Machining Processes Overview

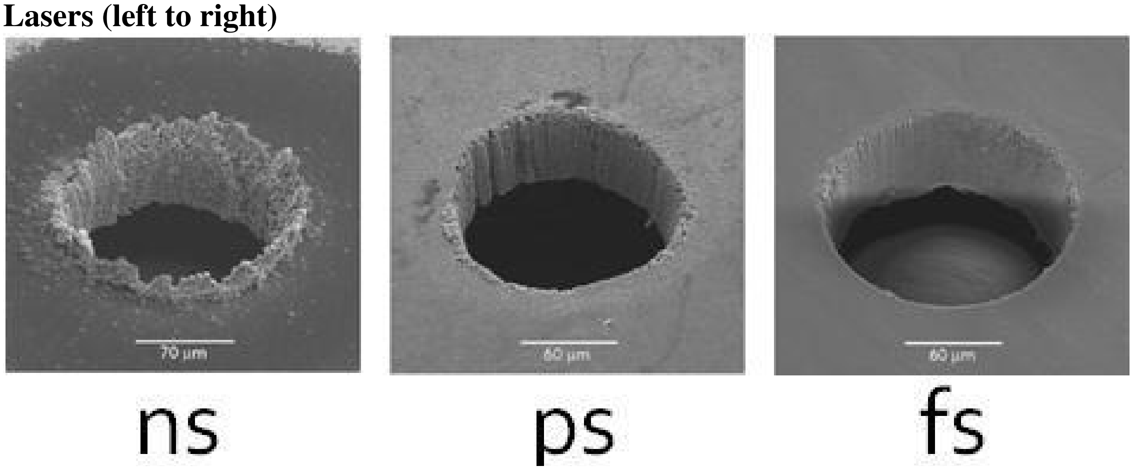
Product Feature	Mfg. Process	Competitive Advantage(s)	Competitive Disadvantage(s)
Cylindrical Hole	Drilling	Short cycle time	Cutting tool cost Hanging burrs
	EDM	Surface finish 2.0Ra or better Burr free entrance and exit	Long cycle time
	Piercing	Short cycle time Surface finish 1.0Ra or better	Long set-up time Pucker
Blind Hole / Counterbore	Milling	Short cycle time	Cutting tool cost Hanging burrs
	EDM	Surface finish 2.0Ra Burr free entrance	Long cycle time

At the project onset, the application of using laser technology to drill fuel injector metering orifices was in development for well over 5 years with disappointing results. The fundamental reason is that, until recently, laser machining systems have been thermal processes imparting heat into the material which modifies the target materials in undesirable ways. Ultrafast laser systems offer processes that are not heat intensive, as they have the capability of athermally ablating materials. The throughput improvements using ultrafast lasers result from the elimination of the post-processing steps in the manufacturing process to remove burrs and pucker and contemplates the lower material removal rates compared to traditional machining techniques. The lack of post processing steps eliminates the variability in the parts and significantly improves yield.

Ultrafast light is a beam of extremely short pulses of energy, each pulse of duration generally in the several hundred femtosecond regime. The brevity of the pulses and the attendant high peak power of the light enables new capabilities across a variety of applications. The most compelling of these capabilities is athermal ablation or the ability to machine micron resolution features in virtually any material without introducing heat to the target. The peak intensity of a laser pulse is effectively the number of simultaneous photons impacting the target. The intensity of a pulse of a given total energy is dramatically elevated (14x) when the overall duration is reduced from 10 picoseconds to 700 femtoseconds.

By introducing the energy to the target in a much more consolidated package, the leading edge of the pulse does not have time to “soak into” the material and raise the temperature. The impacting photons instead raise the energy level of the target so rapidly that it is ionized and liberated from the surface (ablated). Figure 3.1 shows SEM images of holes drilled with laser pulses having durations of different orders of magnitude [ns = nanosecond (10^{-9} seconds), ps = picosecond (10^{-12} seconds), fs = femtosecond (10^{-15} seconds)]. As can be seen, the material that remains after being machined with the ultrafast (fs) laser remains unchanged in shape and material properties.

Figure 3.1: Ø 150µm Holes Cut in a 50µm Thick Silicon Wafer Using ns, ps, & fs Pulse Lasers (left to right)



Raydiance, until acquired by Coherent, was the world‘s leading developer of ultrafast laser technology. Raydiance integrated fiber optic, computing, and software technologies to create the world‘s only fiber based, industrial-grade ultrafast laser. The company was focused on providing transformative, reliable, and cost-effective solutions for the automotive, medical device manufacturing, medical therapies, microelectronics, industrial laser processing, biosciences, and defense markets.

The Raydiance Smart Light™ platform was the only industrial-grade ultrafast laser produced in the United States and the world's only commercial grade system based on robust and readily available fiber optic technology. The integrated software control system facilitates complete, autonomous control of the laser, ready for integration with external systems, which leads to unprecedented performance and reliability standards. Raydiance's application of its unique form of light to cutting-edge materials results (i) in innovation on a daily basis and (ii) in Raydiance being recognized as the unrivaled expert in ultrafast applications. Raydiance's mission was to deliver higher powered and more reliable technologies to the manufacturing market. As part of this project effort, Raydiance developed the processes that take advantage of this expanded capability and knowledge to maximize the lasers efficiency and applicability over a wide range of industrial uses.

Microlution is a company with expertise in micromachining, custom machine design, and multi-axis motion control who has developed a revolutionary breed of machines called micro/mesoscale machine tools (mMTs). These micromachining platforms have been proven in a great number of real world industrial applications.

Microlution developed and released an initial 5-axis, femtosecond laser machining center (ML-5), with the Raydiance Smart Light™ laser and a HP scan head (Figure 3.2). The main goals for this initial system were to optimize part quality, achieve a cycle time requirement put forth by the customer, and achieve the fastest possible time to market (i.e. deliver the machine to the customer as fast as possible in order to meet production needs). Below are some figures and key aspects of the ML-5 system.

ML-5 System Key Components:

- Overall Machine Footprint: L~93" x W~40" x H~84"
- Base Construction: Precision ground granite
- Drive Technology: Ironless linear motors
- Bearings: Super precision, caged, linear ball guides
- Position Feedback: Sealed linear glass scales from Heidenhain (0.005 micron resolution absolute position feedback)
- Laser Enclosure: Class 1 enclosure with no direct line of sight to the laser

Figure 3.2: Microlution ML-5 System Overview

ML-5 System Key Points:

- Precision ground granite is used for the machine base due to its stable thermal and inertial characteristics
- Raydiance's Output Module is mounted directly to the granite base to promote stability during the beam delivery
- The beam is redirected three times before reaching the HP scan head. Two fixed and one moving optic will be used to deliver the beam along the path
- The trunnion selected allows for the part to be fixtured such that the area which needs to be machined is in line with the tilt axis of rotation. This allows for minimum movement of the Y and Z axes
- To further minimize HP scan head movement and to simplify the beam delivery path, the X & Y stages are mounted underneath the trunnion
- The Y stage moves the trunnion table to position for robot load and unload
- Ability to incorporate a fiber optic beam delivery will allow adaptability to other applications

Thus, the existing ML-5 system offers a robust platform well-integrated with the Radiance laser. Further activities required to meet the objectives of the project focused on enhancements to ensure high part quality and achieve a reduced cycle time. Development in the key areas of control synchronization, machine movement, and parallel processing / machine architecture led to higher laser utilization, higher overall system productivity, and increased commercial viability for the fuel injector application within this project, as well as for other applications and industries.

Delphi has a long history of developing fuel systems for automotive applications, with a worldwide customer base for fuel injection systems and full engine management systems. Accordingly, Delphi continuously builds on years of experience from previous injector development, verification testing, and full-scale validation based on vast experimental facilities, analytical tools and manufacturing facilities. Delphi was therefore ideally suited to implement and assess the system's capabilities against the current state-of-the-art manufacturing techniques.

In response to increased mandates for improved fuel economy and reduced CO_2 emissions, passenger cars are increasingly implementing gasoline direct injection engines that deliver fuel directly into the engine cylinder instead of the intake port. These GDi engines enable increased engine compression ratio and/or better compatibility with turbocharging to offer substantial engine efficiency improvements during typical driving. Turbocharged GDi engines can be downsized to improve fuel economy by 10% or more without any sacrifice in vehicle performance or drivability. However, fuel delivery directly into the cylinder substantially increases the spray generation and flow requirements of GDi injectors compared to port fuel injectors. Key requirements include the ability to precisely meter a desired quantity of fuel over wide operating conditions, a well-atomized spray to promote complete vaporization of the fuel before combustion begins, proper spray targeting with low fuel penetration to ensure that liquid fuel does not strike solid surfaces such as valves, spark plugs, or the cylinder wall or piston top, and the ability for the injector tip to survive within the combustion chamber with excellent durability.

Simultaneously meeting these GDi injector requirements involves careful design of the product and manufacturing processes. Development of the metering orifices includes precise determination and control of many parameters defining the characteristics of through-holes and counterbores. Successfully developed products thus require careful analysis and cooperation between highly-skilled product and process engineering teams.

Metering orifices are currently machined using multiple operations. Transferring the work piece between machining platforms reduces cycle time and presents challenges in maintaining precision of the complex shapes that the orifices comprise. Based on the fundamental capabilities of ultrafast laser micromachining, Delphi proposed to develop and verify a prototype platform for machining metering orifices. By applying Delphi‘s production manufacturing expertise, it is expected that this platform will offer a “game changing” manufacturing process to machine GDi fuel injector metering orifices with high precision and fast cycle time. It is also expected that the technology improvements developed within this project can be subsequently translated by the project partners to improvements in micromachining for customers in a broad range of other industries.

4. Results and Discussion

The project was executed in two phases, Budget Periods 1 and 2. The effort in Budget Period 1 involved process development and individual process segment demonstration for GDi fuel injector metering orifices. The prototype micromachining platform was specifically applied by Delphi to manufacture these GDi fuel injector metering orifices. This allowed for evaluation of the prototype system against rigorous, real-world requirements in an application aimed at significant global energy and CO_2 reduction.

The effort in Budget Period 2 involved process development and individual process segment demonstration across other industries, such as electronic and biomedical. The objectives of the project were designed to allow for rapid implementation of other materials and applications across these industries. Microlution used the multi-application testbed to accommodate new materials, part geometries, and processing requirements for specific electronic and biomedical industrial applications. A successfully-executed project resulted in a manufacturing method offering reduced process steps and energy consumption for hard-to-machine materials across multiple markets.

BUDGET PERIOD 1 (Task 1.0 – Task 4.0)

Task 1.0 Laser and Scan Head Development

Subtask 1.1 Development Workstation Design and Build

Design and construct the high performance scan head to provide significant improvements to the motor and control hardware and cooling methods. The deliverable from this effort will be a performance demonstration of the enhanced scanning head. The target is a rotational speed > 200Hz at an attack angle > 80%.

Milestone 1.1.1 Demonstrate scanning head meets or exceeds performance targets.

At the project onset, Raydiance reviewed the objectives of the HP scan head project with the supplier, Arges, and completed a concept design review with Delphi and Arges. The agreed upon technical approach incorporated substantial reduction in mass and inertia of the moving components in order to support the high rotational speed and enable a greater attack angle.

Arges completed the HP scan head design study and prototyping to substantially reduce the inertia of the moving components with a target inertia ≤ 0.25x that of the existing design. The results of the design study were reviewed by the project technical team and the decision was made to proceed with the integration of the low inertia solution into the HP scan head with a rotation speed performance target of 3x the existing design.

Arges assembled, tested, and shipped the HP scan head to Raydiance. The HP scan head was installed onto the micromachining process development workstation, fully tested, and inspected.

Test Conditions and Method of Measurement:

Arges performed an initial evaluation of the HP scan head prior to its shipment to Raydiance using the standard scan head as a baseline. The following instrumentation was used to measure the positional accuracy of the procession components: a sine wave function generator, a digital oscilloscope, and a laboratory power supply. Arges procession speed capability data for the standard scan head and the HP scan head at attack angles of 50% and 100% is shown in Table 4.1.

Table 4.1: Arges Procession Speed Capability Data

	1st Gen Precession Unit	2nd Gen Precession Unit
Freq. limit for harmonic operation at ±7.5°m	80 Hz	300Hz
Phase shift at limit for harmonic operation at ±7.5°m	9°	20°
Amplitude loss at limit for harmonic operation at ±7.5°m	1%	1%
Freq. limit for harmonic operation at ±15.0°m	65 Hz (estimated)	225Hz
Phase shift at limit for harmonic operation at ±15.0°m	n/a	15°
Amplitude loss at limit for harmonic operation at ±15.0°m	n/a	1%

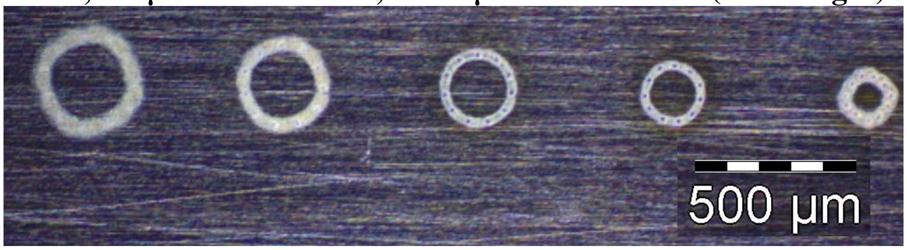
* 1st Gen Precession Unit → Standard Scan Head, 2nd Gen Precession Unit → HP Scan Head, ±7.5°m → 50% attack angle, ±15°m → 100% attack angle.

Raydiance observed the roundness of the laser ablation using visual standards (circularity templates). The standard scan head (baseline) at attack angles over 60% at 100Hz had noncircular patterns. Attack angles over 75% at 100Hz had gross and clearly visible diamond or square characteristics. Attack angles over 60% required a reduction in the rotational speed to maintain circularity. Circularity was measured by placing a perfect circle drawn in software over the center of the laser ablation marks.

Raydiance's analysis of the HP scan head was performed by firing the laser at a low repetition rate over a single circle drawn by the HP scan head at various attack angles and revolution speeds. Resulting circles were examined with a high power measuring optical microscope. At focus, results generally appear better than out of focus results.

Focus patterns examples from 400µm below focus to 400µm above focus are shown in Figure 4.1. The parts were run at 250Hz at 100% of the maximum attack angle. While the at focus part appears qualitatively good, the out of focus diamond shapes would impact hole quality.

Figure 4.1: Focus Pattern Examples – 400μm Below Focus, 200μm Below Focus, At Focus, 200μm Above Focus, & 400μm Above Focus (left to right)



Test Results and Milestone Verification Data:

The HP scan head performance was confirmed over a range of rotation speeds from 100Hz to 300Hz and large attack angles from 60% to 100%. At an attack angle of 60% of the maximum, the HP scan head produced circular motion at 300Hz, the maximum revolutions per second tested. At an attack angle of 80% of the maximum, the HP scan head produced circular motion at ~200Hz. At an attack angle of 100% of the maximum, the HP scan head produced circular motion at ~150Hz. The HP scan head met the performance goals by achieving > 200Hz rotation frequency at an attack angle > 80%. Baseline hole drilling was demonstrated with the HP scan head at 100Hz.

Figure 4.2: Speed of Rotation vs. Attack Angle w/ Work Piece 400μm Below Focus

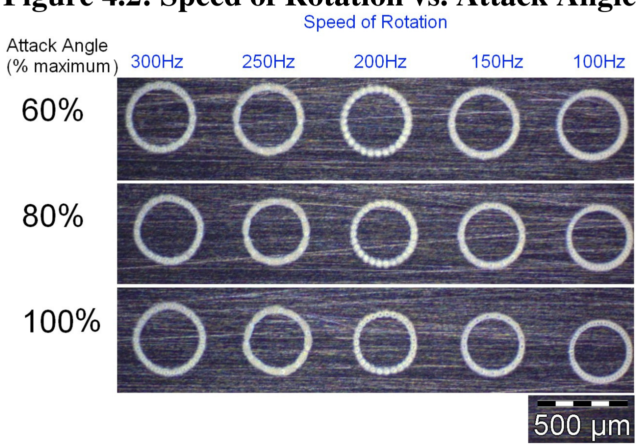
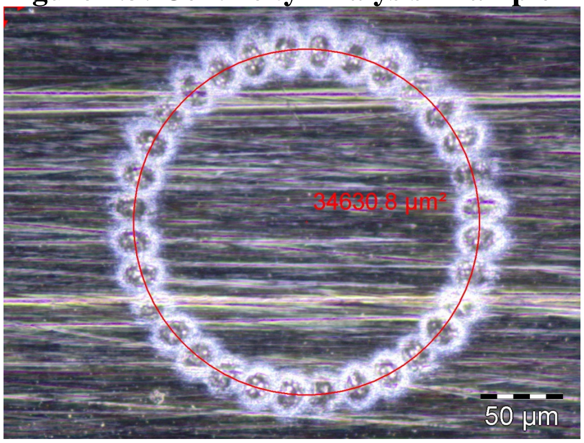


Figure 4.3 shows an example of centricity analysis. Circles were marked. The example was performed at a 100% attack angle and 100Hz. Using a measuring microscope, a circle was drawn through the laser ablation marks. The marks were inspected for deviations from ideal circularity.

Figure 4.3: Centricity Analysis Example



Subtask 1.2 Material Removal
The deliverable from this effort will be a demonstration of the best performing laser system configuration for spray hole drilling fuel injector nozzle seats. The target is a 50% cycle time reduction from the current system with no degradation in quality.
Milestone 1.2.1 Demonstrate 50% CT reduction for laser drilling spray holes.

The goal is to substantially improve the results of the drilling process by increasing the ablation rate by at least a factor of 2 and improving the diameter tolerance repeatability by 50%. The proposed game-changing laser drilling process can be achieved through the development of three major elements: the Raydiance ultrafast laser, the multi-axis beam scanner, and the laser drilling process parameters.

Test Conditions and Method of Measurement:

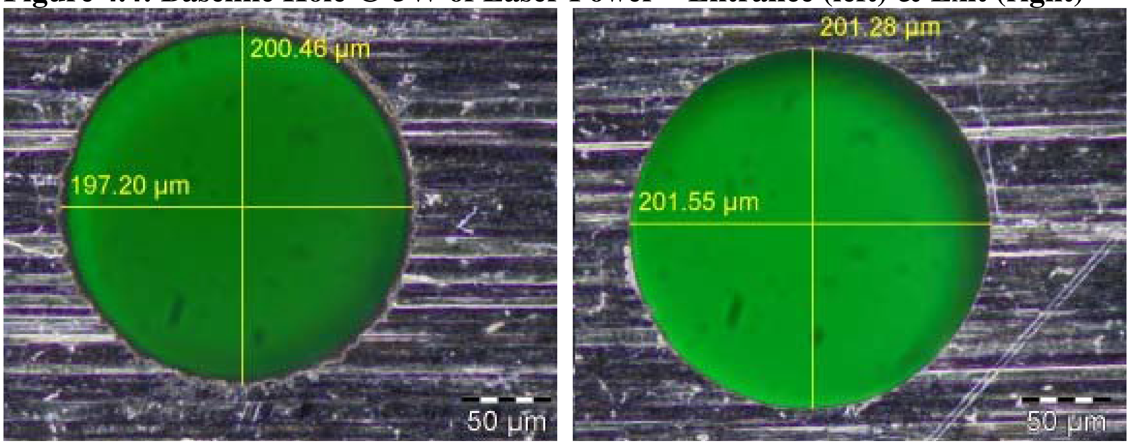
A micromachining process development workstation was configured to facilitate initial testing of the enhanced ultrafast lasers and the development of the drilling process parameters. This workstation includes a next generation Raydiance ultrafast laser with four times the average power and two times the pulse energy of the current Raydiance commercial laser. The workstation also has a current generation multi-axis beam delivery scanning system. The Raydiance laser can be programmed to operate over a wide range of pulse energies and repetition rates.

The laser and workstation were used to baseline the current fuel injector drilling process and characterize the speed and quality benefits of higher power laser operation. Raydiance baselined the GDi spray hole drilling process at average laser powers of 5W, 10W, and 20W. At each power level, the optimal drilling speed was determined using the same standard drilling algorithm. Raydiance did not have access to Delphi's hole drilling algorithm, so a preexisting algorithm (developed for use on a 5W system, designed for a 200µm diameter hole through 250µm thick 316 stainless steel) was selected. An optical microscope and a white light interferometer were the methods of measurement used.

Test Results and Milestone Verification Data:

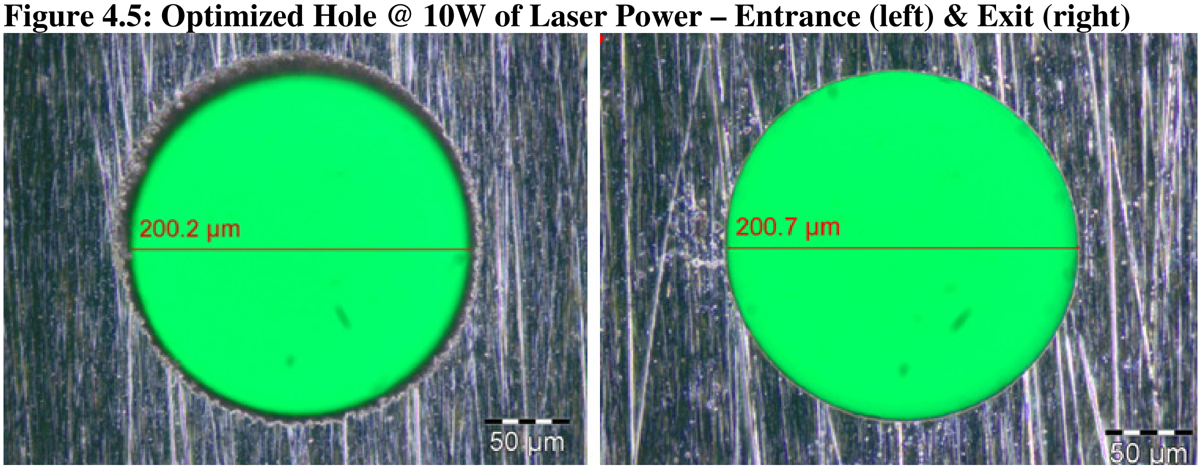
The maximum material removal rate was confirmed to scale linearly with laser average power. Drilled samples were sectioned, etched, and inspected for any signs of deleterious effects from the higher laser power drilling. No deleterious effects were realized from the higher laser power drilling.

Figure 4.4: Baseline Hole @ 5W of Laser Power – Entrance (left) & Exit (right)



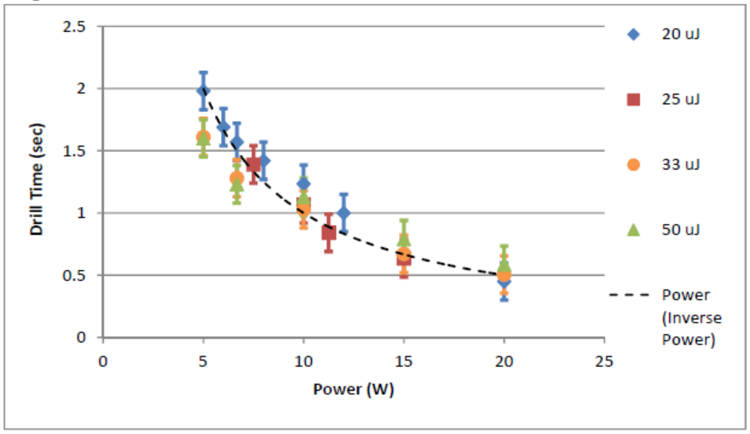
An optimization study of GDi spray hole drilling was completed at average laser powers of 5W and 10W. The material removal rate was confirmed to scale linearly with laser average power. A preexisting algorithm for a 5W laser had a 2 second drill time. At 10W average power, the same hole dimensions and quality was produced in 1 second. Optimization work further reduced the 10W drill time to 0.72 seconds. Metrology work on the hole sidewalls showed no measurable difference between the 5W, 2 second and 10W, 1 second GDi spray holes. The optimized 10W, 0.72 second routine demonstrated slight and correctable differences in sidewall profile and quality. Additional laser drilling process development at higher powers resulted in faster drilling times with equivalent hole quality and dimensional repeatability. For example, drilling time further reduced to 0.5 seconds using a 20W laser with no apparent degradation of hole quality.

Figure 4.5: Optimized Hole @ 10W of Laser Power – Entrance (left) & Exit (right)



Through a combination of increased laser power on target and laser drilling process development, the hole drilling times have been reduced from 2 seconds per hole with the baseline 5W laser and algorithm to less than 1 second per hole using the 10W laser, more than a 50% cycle time reduction. A linear relationship was demonstrated between hole drilling rate and laser power. During evaluation of the HP scan head, further cycle time reduction was achieved with increased laser power.

Figure 4.6: Measured Minimum Drill Time vs. Laser Power & Pulse Energy



Delphi is currently making production parts with a Raydiance 10W laser. To demonstrate production feasibility using higher laser power, production fuel injector nozzle seat blanks were provided by Delphi and used to drill holes at 15W and 20W.

Subtask 1.3 Counterbore Process Development
The deliverable from this effort will be demonstration of laser generation of nozzle holes including a spray hole and counterbore in less than 8 seconds, which passes spray tests described in the Project Scope.
Milestone 1.3.1 Laser drill c-bore and spray hole < 8 seconds and pass spray criteria.

The goal was to demonstrate laser generation of fuel injector nozzle holes including a spray hole and a counterbore using production material, heat treated 440A stainless steel.

Test Conditions and Method of Measurement:

A set of experiments was designed to investigate the full range of process parameters for ultrafast laser machining of counterbores in flat material samples. The process development work focused on moving beyond repeated raster patterns to spiraling 3D patterns to reach the target throughput times and wall taper requirements. Varying laser focused spot size and focus parameters were explored to help improve volume removal rates, attempt to limit and control surface texturing, and understand the parameters leading to pinhole formation. The design of experiments found mutually exclusive process conditions capable of higher quality material removal in counterbores in excess of 200µm deep.

During the first phase of designed experiments, the following elements were identified as the technical challenges; sidewall taper, debris removal, overall counterbore geometry (side wall and bottom), cycle time, quantifying the robustness of the process, minimizing the counterbore wall/bottom intersection trench, continued improvement of the ablation process surface roughness, and milling of counterbores on 3D surfaces. The next phase of the process development work focused on improving the geometric shape of the counterbore while reducing the cycle time. The work to control the wall taper found numerous process conditions which helped to reduce the wall taper. Reducing the wall taper extended the allowable counterbore depth from ~275µm to 400µm. A serviceable and low cost process gas was identified and the ablation process was found to be robust and repeatable. Optimization of the process gas dynamics improved debris removal rates considerably. This allowed for more aggressive material removal and a reduction of cycle time. 400µm deep counterbores with spray holes in under 8 seconds total drilling time were demonstrated in flat material samples. The geometry of the counterbore includes the desired flat bottom, slightly tapered side walls, and a trench at the bottom of the side wall.

Test Results and Milestone Verification Data:

Preliminary development work to transfer the counterbore machining process from the stainless steel sheet stock (flat material) to the machined fuel injector nozzle seat blank was completed. During the transfer, the machining quality was observed to degrade dramatically. The primary issue was the formation of pin holes in the bottom surface as the machining process progresses. This pin-holing was observed to become progressively worse as the machined counterbore hole got deeper. During the investigation of the cause of the machining quality change, it was discovered that the laser machining quality was material dependent.

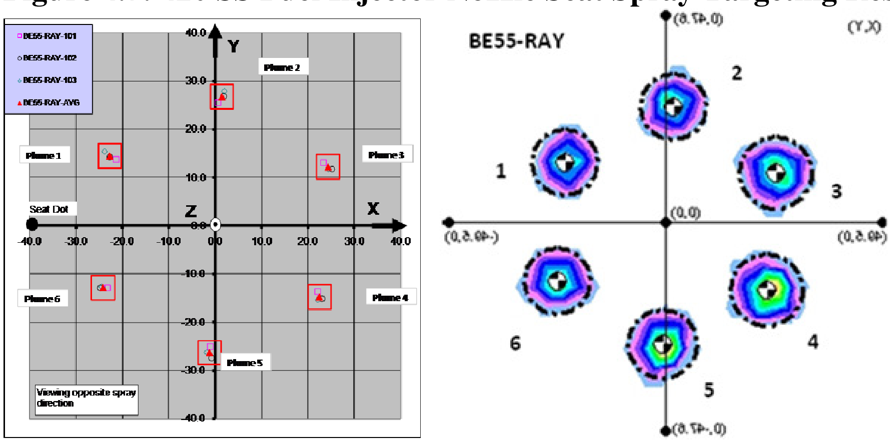
An experimental material study of various stainless steel alloys was conducted to identify specific materials and fabrication processes that are compatible with counterbore-by-laser. Stainless steel material samples were analyzed to determine the root cause of the ablation variation and determine a possible path to material selection. The current material used for the machined fuel injector nozzle seat was found to contain large primary carbides along grain boundaries throughout the material as well as dispersed secondary carbides within the grains. These large carbides also have some orientation along the rolling direction of the material. This inhomogeneous material may cause microscopic variation in localized regions where the laser is impacting the material, which could result in the inconsistent laser effect on the material. A heat treatment prior to laser drilling was proposed which would result in a redistribution of the carbides and a more even microstructure. This heat treatment should result in a very uniform martensitic microstructure with an even and dispersed secondary carbide distribution. Samples of the machined fuel injector nozzle seats were heat treated and laser drilled and there was an improvement in the surface quality, but the quality was not equal to the flat samples previously demonstrated.

During the experimental study of various stainless steel materials, an alternative material (420 stainless steel) was found that produced high quality laser drilled counterbores. Machined fuel injector nozzle seat blanks were produced using this alternative material. Laser drilled counterbores and spray holes were then added on Raydiance’s development workstation. Heat treated 440A stainless steel samples were also manufactured for analysis.

It is important to note that both sets of fuel injector nozzle seat blanks needed to have a machined "flat" added prior to laser drilling to control depth, adding a milling process step (increasing cycle time and cost). The samples were then sent to Delphi to complete the manufacturing process and further evaluate the samples.

Delphi completed the fabrication of the 420 stainless steel fuel injector nozzle seats and built them into spray mules (injector assemblies). The spray mules were spray tested with good results. Spray shape was largely unchanged in comparison to the standard production fuel injector nozzle seat, which was not fully expected. The 420 stainless steel fuel injector nozzle seat was not very good from a targeting perspective, but that was expected.

Figure 4.7: 420 SS Fuel Injector Nozzle Seat Spray Targeting Results



The heat treated 440A stainless steel samples that were sent to Delphi had exaggerated sidewall serrations and a rougher counterbore bottom surface in comparison to the 420 stainless steel samples. These samples were not built into spray mules based on the learnings from the 420 stainless steel samples.

This completed demonstration of all laser drilled fuel injector nozzle seats with successful spray test offers one possible route to the volume production of laser drilled fuel injector nozzle seats. However, 420 stainless steel is not desirable for use in the production of the fuel injector nozzle seat as its ability to attain the required hardness values with production variation is not sufficient. The requalification of fuel injector nozzle seats using a different material is a lengthy process and outside of the technical project scope and planned timeline of this contract.

In addition, the cycle time to laser drill a counterbore and spray hole was ~13 seconds in a 420 stainless steel sample as well as a heat treated 440A stainless steel sample, which exceeds the less than 8 second target. This was due to debris management challenges and the fact that a less aggressive cycle time was necessary to maintain part quality. While a cycle time greater than 8 seconds is not viable for Delphi, it may be acceptable in other market applications.

Due to the non-viability of laser drilled counterbores described above, the team sought an alternative method for counterbore machining with the desire to consolidate the counterbore machining operation with laser drilling of the through holes onto a single micromachining platform. This is a shift in the industry paradigm that micromachining of the through hole and counterbore have to be completed on two different platforms. High-speed milling of the counterbore was chosen as an alternative to laser drilling as it is most commonly used in the industry to manufacture blind features of this size range. Ultimately, a high-speed milling spindle was therefore added to the enhanced laser chassis. Combining drilling and milling operations on a single hybrid enhanced laser chassis offers a fast, high precision manufacturing method that provides substantial reduction in cycle time and energy consumption compared to the baseline method and has shown to produce parts meeting Delphi's established performance targets and product quality characteristics within a smaller manufacturing footprint. The cycle time (a key performance criterion) to generate a laser drilled spray hole and a milled counterbore was demonstrated in approximately 2.4 seconds.

Figure 4.8: C'Bore Ablation – Flat Sheet Stock (left) & Machined Fuel Injector Nozzle Seat (right)

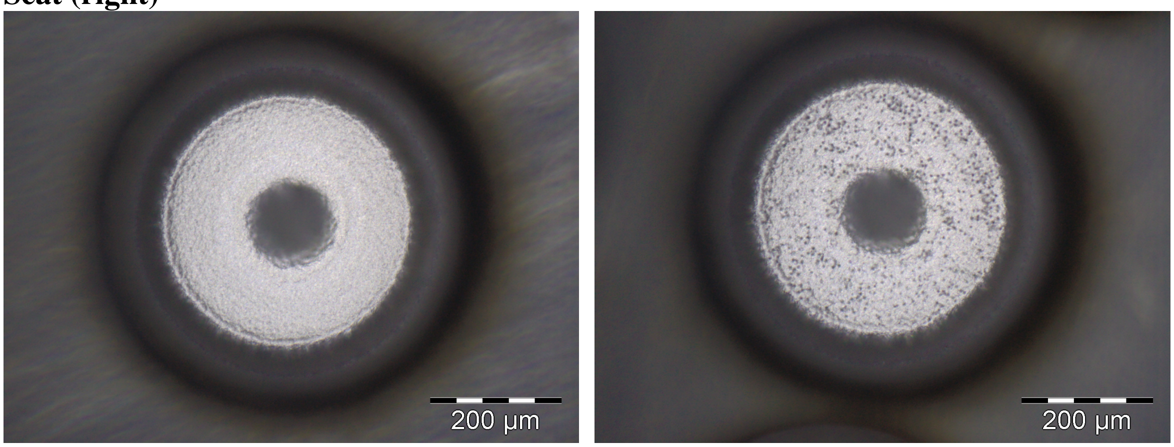
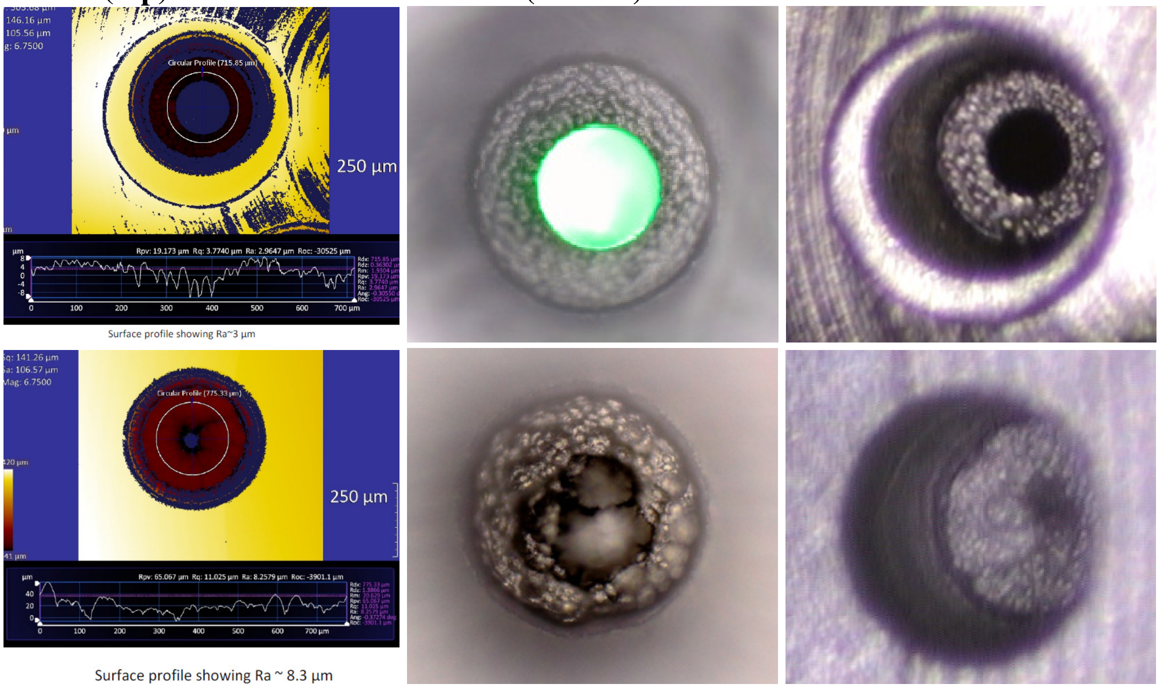


Figure 4.9: 3D Laser Drilling of C'Bore in Machined Fuel Injector Nozzle Seat Blank – 420 SS (top) & Heat Treated 440A SS (bottom)



Task 2.0 Work Holding and Automation

Subtask 2.1 Develop Work Holding Concept and Datum Structure

Develop precision work holding and automation concepts to further enhance the application of ultrafast laser technology to micromachining custom shaped holes and counterbores. The deliverable from this effort will be a work holding concept selection matrix and test plan.

Significant effort was devoted to developing work holding concepts that would result in improvements in dimensional capability of spray hole to counterbore concentricity, reduction in cycle time, improved uptime, and improvement in the capability to remove ablated material.

Redesign, development, and testing occurred to improve work holding from the 5 piece collet – 3 jaw chuck concept used in the TRL 4 platform to the 1 piece collet – 3 jaw chuck concept. This development effort resulted in tighter dimensional capability of spray hole to counterbore concentricity and increased uptime primarily due to improved capability to remove ablated material.

In parallel with this development effort, the cross functional team generated a work holding concept selection matrix using the Pugh method. Pugh Concept Selection is a quantitative technique used to rank the multi-dimensional options of an option set. It is frequently used in engineering for making design decisions, but can also be used to rank investment options, vendor options, product options, or any other set of multidimensional entities. A basic decision matrix consists of establishing a set of criteria options which are scored and summed to gain a total score which can then be ranked.[i]

The results of the Pugh analysis were unexpected. The Pugh analysis ranked the HSK style chuck and the 1 piece collet – 3 jaw chuck concepts comparable except for one important category, cycle time. The HSK style chuck is quick change by design, readily adaptable, and expected to yield faster cycle time. One expected disadvantage of the HSK style chuck concept is some degradation in dimensional accuracy over the 1 piece collet – 3 jaw chuck concept.

Table 4.2: Concept Selection Matrix (Initial)

Criteria	Criteria Weighting	Concepts				
		5 Piece Collet 3 Jaw Chuck	1 Piece Collet 3 Jaw Chuck	Colletless Chuck	3R Style Chuck	HSK Style Chuck
Implementation	3	1	1	-1	-1	1
Load/Unload Time	8	-1	-1	0	-1	1
Accuracy/Consistency	10	0	1	1	1	0
Cost	6	-1	0	0	0	1
Lifecycle Analysis	1	-1	1	1	1	0
Data/Results	10	-1	1	1	1	0
Durability	5	0	1	0	0	0
Upgradabililty	3	0	0	-1	1	1
Serviceability	3	-1	0	1	0	1
Consumable Usage	5	-1	0	1	1	1
Strerility	6	-1	1	1	1	1
Sum of Positives		1	6	6	6	7
Sum of Negatives		7	1	2	2	0
Sum of Sames		3	4	3	3	4
Weighted Sum of Positives		3	35	35	35	34
Weighted Sum of Negatives		-39	-8	-6	-11	0
Overall Weighted Score		-36	27	29	24	34

The HSK style chuck concept was further developed by incorporating a taper locking collet with the HSK style chuck. Work piece clamping is accomplished when force is applied to the self-locking collet thereby forcing the collet into the chuck which generates clamping force to the work piece. This approach still requires rough location of the fuel injector nozzle seat using a method similar to TRL 4. Once the fuel injector nozzle seat has been loaded, clamped, and laser drilled, the 10W laser will then mark the fuel injector nozzle seat with an orientation feature that will be used for precise positioning of the work piece. This taper lock fixturing operation takes place outside of the laser process. Once the raw fuel injector nozzle seat is in the taper locked collet and pressed into the HSK style chuck, a pivot arm picks up the HSK style chuck with the raw fuel injector nozzle seat and an HSK style chuck with a finished fuel injector nozzle seat (in the machine) and simply exchanges the two. The pick-n-place is estimated to be done within 3 seconds, as opposed to the current 6 second cycle time to exchange the fuel injector nozzle seats.

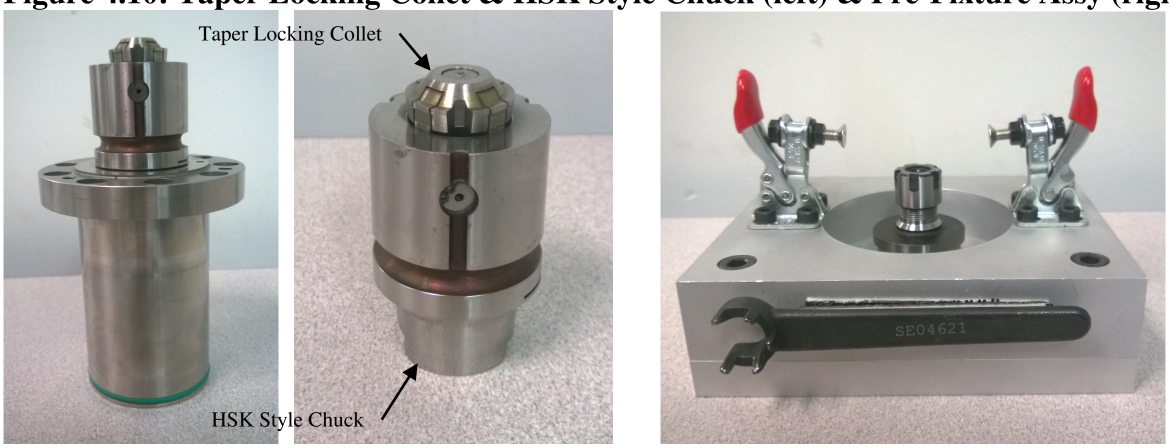
A test plan was developed to evaluate the performance of the HSK style chuck concept against selection and performance criteria. Phase 1 consisted of evaluating part accuracy using the HSK fixturing concept outside of the machine. Phase 2 consisted of HSK style chuck repeatability testing using the enhanced laser chassis.

Subtask 2.2 Automated Work Holding Demonstration
The deliverable from this effort will be a report containing the concept selection matrix, tool trial data, results summary, and concept recommendation.
Milestone 2.2.1 Present concept selection matrix, tool trial data, and results summary.

The taper locking collet and HSK style chuck (inner and outer work holding collet assemblies) were constructed. A more complex height datum support post design was necessary to provide part support when using the high-speed milling spindle that was added to the enhanced laser chassis. The height datum support post is retractable so that the laser does not ablate the pin during the laser drilling process.

The scope of work required to pre-fixture the fuel injector nozzle seat before installation into the taper locking collet became more complicated and time consuming than anticipated. The pre-fixture details (outside of the enhanced laser chassis) were also constructed.

Figure 4.10: Taper Locking Collet & HSK Style Chuck (left) & Pre-Fixture Assy (right)



Delphi experienced countless supplier delays with the inner and outer work holding collet assemblies due to the unexpected difficulty in manufacturing them. This drove up the cost and caused the cross functional team to reevaluate the work holding concept selection matrix. The ranking of the cost criteria of the HSK style chuck was revised from “1” to “-1” as seen in Table 4.3.

Table 4.3: Concept Selection Matrix (Revised)

Criteria	Criteria Weighting	Concepts				
		5 Piece Collet 3 Jaw Chuck	1 Piece Collet 3 Jaw Chuck	Colletless Chuck	3R Style Chuck	HSK Style Chuck
Implementation	3	1	1	-1	-1	1
Load/Unload Time	8	-1	-1	0	-1	1
Accuracy/Consistency	10	0	1	1	1	0
Cost	6	-1	0	0	0	-1
Lifecycle Analysis	1	-1	1	1	1	0
Data/Results	10	-1	1	1	1	0
Durability	5	0	1	0	0	0
Upgradabililty	3	0	0	-1	1	1
Serviceability	3	-1	0	1	0	1
Consumable Usage	5	-1	0	1	1	1
Strerility	6	-1	1	1	1	1
Sum of Positives		1	6	6	6	6
Sum of Negatives		7	1	2	2	1
Sum of Sames		3	4	3	3	4
Weighted Sum of Positives		3	35	35	35	28
Weighted Sum of Negatives		-39	-8	-6	-11	-6
Overall Weighted Score		-36	27	29	24	22

Based on the results of the revised Pugh analysis, the cross functional team took a closer look at the viability and benefits of the colletless chuck concept. Due to the immediate availability of the 1 piece collet – 3 jaw chuck fixture, the consensus was to use the 1 piece collet – 3 jaw chuck design to complete Subtask 2.2 (Automated Work Holding Demonstration), Subtask 4.1 (Integrated and Component Processing), and Subtask 4.2 (Valve Seat Development) with a long-term plan to further develop and implement the colletless chuck concept. The colletless chuck concept is optimum because it is a single piece fixture by design.

Test Conditions and Method of Measurement (HSK Style Chuck):

Delphi received the taper locking collet and HSK style chuck at the end of February 2014 and completed the overall assessment. HSK style chuck repeatability was checked on the Taylor Hobson Talyrond 595 because the 1 piece collet – 3 jaw chuck fixturing was already installed on the enhanced laser chassis when the HSK tooling arrived.

Test Results and Milestone Verification Data (HSK Style Chuck):

The HSK style chuck showed poor fixturing repeatability outside of the desired tolerance range, supporting the conclusion that the HSK style chuck concept is not a viable option for this application.

Test Conditions and Method of Measurement (1 Piece Collet – 3 Jaw Chuck):

The initial test plan developed to evaluate the performance of the HSK style chuck concept against selection and performance criteria was revised for the 1 piece collet – 3 jaw chuck concept. A generic part with a symmetric hole pattern was targeted using techniques previously developed as well as new and improved math based techniques and machine tool set-ups.

Figure 4.11: Test Plan (1 Piece Collet – 3 Jaw Chuck)

The 3 jaw chuck locks the 1 piece collet and part into place.
2.1.1. Measure the part location in the 1 piece collet independent of the machine fixture.
2.1.2. Manually clamp a part into the 1 piece collet.
2.1.3. Manually clamp the 1 piece collet into the enhanced laser chassis trunion.
2.1.4. Mill the counterbores and laser drill the flow holes.
2.1.5. Repeat steps 2.1.2 thru 2.1.4. for a total of 30 parts.
2.1.6. Measure the 30 parts on the Werth CMM.
2.1.7. Evaluate the accuracy of the holes compared to the process baseline.

The capability run was executed to test the 1 piece collet – 3 jaw chuck work holding concept, but also a culmination of other enhanced laser chassis attributes including thermal stability. No warm-up procedures were used as the capability run was started after the enhanced laser chassis had been idle for over 2 hours. It is important to note that operation of the current production equipment with no warm-up would result in variation caused by thermal effects, producing parts that are out of tolerance.

Test Results and Milestone Verification Data (1 Piece Collet – 3 Jaw Chuck):

Delphi executed the test plan on the enhanced laser chassis using the 1 piece collet – 3 jaw chuck concept. Thirty-four fuel injector nozzle seats were produced to evaluate short-term process capability of critical features. This capability was compared to the process capability of the production machine. Key features evaluated included counterbore true position and spray hole to counterbore concentricity (X and Y).

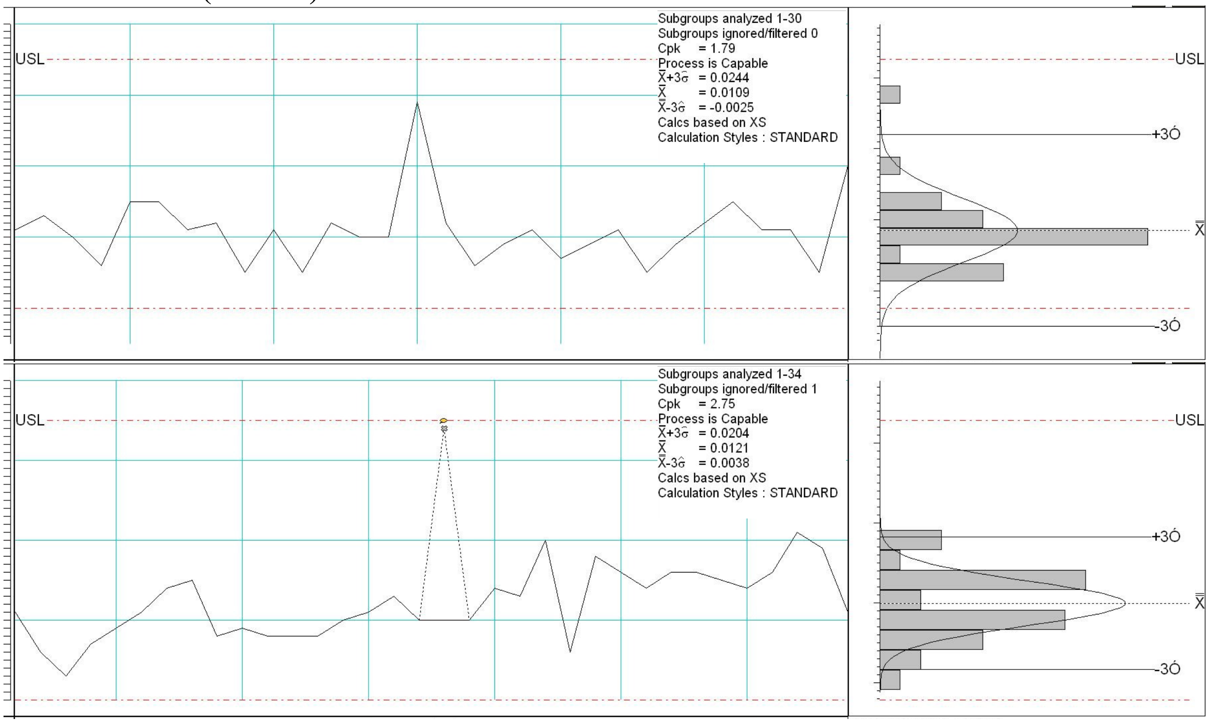
Table 4.4 shows the process capability summary of the counterbore and laser drilled hole positions with respect to the current print tolerances. Six holes were measured on each fuel injector nozzle seat by the Werth CMM. The results using the 1 piece collet – 3 jaw chuck design on the enhanced laser chassis show significantly less variation of the spray hole to counterbore concentricity compared to the production baseline. The counterbore true position variation is minimal as expected.

Table 4.4: Process Capability Data – Production Baseline (top) & Enhanced Laser Chassis (bottom)[ii]

Feature	Production Baseline													
	Process Capability													
	Hole 1		Hole 2		Hole 3		Hole 4		Hole 5		Hole 6		Mean	
	C_p	C_{pk}	C_p	C_{pk}	C_p	C_{pk}	C_p	C_{pk}	C_p	C_{pk}	C_p	C_{pk}	C_p	C_{pk}
Counterbore X Position	3.60	2.95	2.30	1.84	1.82	1.75	2.81	2.51	2.69	2.19	2.48	2.18	**2.62**	**2.24**
Counterbore Y Position	2.42	2.09	2.73	1.84	2.61	2.04	2.77	2.32	3.08	2.80	2.81	2.33	**2.74**	**2.24**
Counterbore True Position	-	2.62	-	1.49	-	1.79	-	2.46	-	2.25	-	2.07	-	**2.11**
Spray Length	2.87	2.79	3.13	2.42	2.41	2.06	3.13	2.77	3.10	2.78	3.21	2.41	**2.98**	**2.54**
Spray to Counterbore X	4.74	2.66	3.76	3.62	3.76	3.55	5.90	5.87	4.54	4.17	3.58	2.68	**4.38**	**3.76**
Spray to Counterbore Y	3.36	3.07	2.57	1.88	4.20	2.96	3.41	3.09	3.12	3.02	3.64	3.02	**3.38**	**2.84**
Feature	**1 Piece Collet - 3 Jaw Chuck on Enhanced Laser Chassis**													
	Process Capability													
	Hole 1		**Hole 2**		**Hole 3**		**Hole 4**		**Hole 5**		**Hole 6**		**Mean**	
	C_p	C_{pk}	C_p	C_{pk}	C_p	C_{pk}	C_p	C_{pk}	C_p	C_{pk}	C_p	C_{pk}	C_p	C_{pk}
Counterbore X Position	2.04	1.69	1.88	1.63	2.15	1.93	2.07	1.72	2.39	2.20	2.19	2.01	**2.12**	**1.86**
Counterbore Y Position	4.21	3.48	4.39	2.64	3.76	2.67	4.58	3.57	5.54	4.87	3.70	3.22	**4.36**	**3.41**
Counterbore True Position	-	1.68	-	2.41	-	2.75	-	2.14	-	2.42	-	2.23	-	**2.27**
Spray Length	4.93	4.25	4.85	4.70	4.07	3.96	4.30	3.89	3.96	3.76	4.30	4.02	**4.40**	**4.10**
Spray to Counterbore X	8.30	8.15	9.63	9.44	5.23	5.10	4.22	4.22	8.02	7.91	4.01	3.96	**6.57**	**6.46**
Spray to Counterbore Y	6.33	6.25	7.77	7.52	8.60	8.39	10.94	10.68	12.04	11.73	6.02	5.76	**8.62**	**8.39**

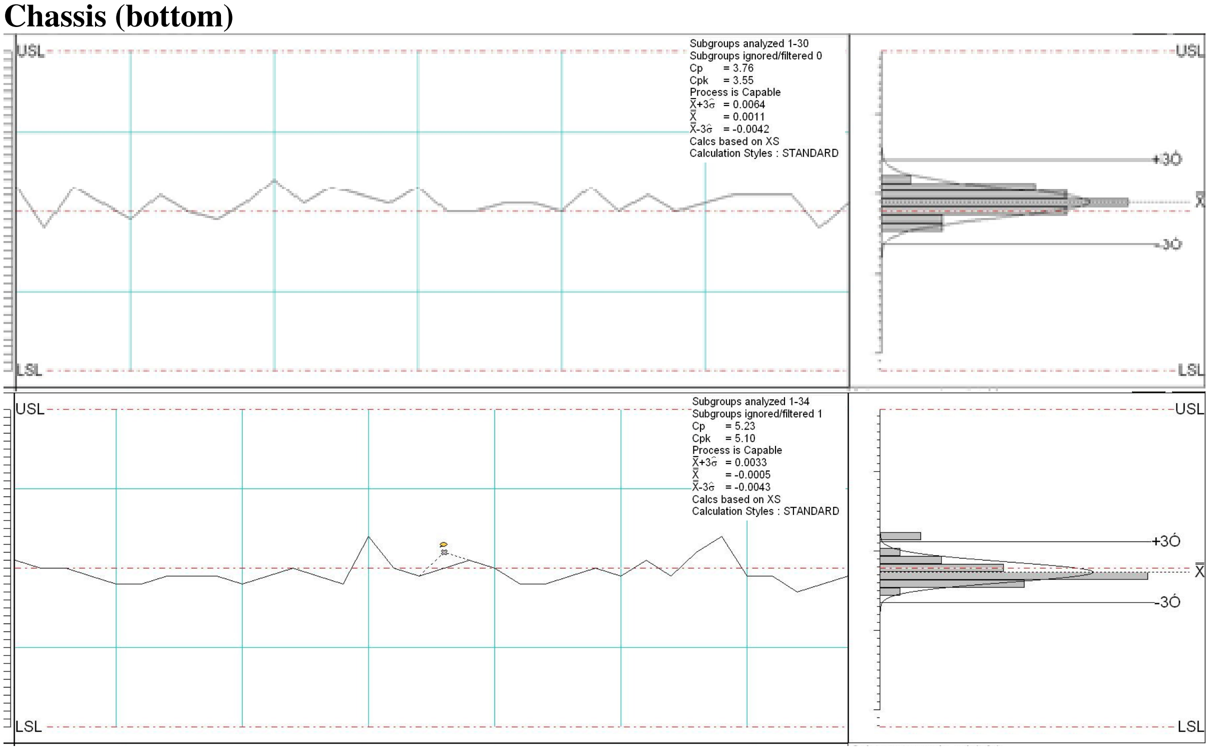
Index	Description
$\hat{C}_p = \frac{USL - LSL}{6\hat{\sigma}}$	Estimates what the process is capable of producing if the process mean were to be centered between the specification limits. Assumes process output is approximately normally distributed.
$\hat{C}_{p,lower} = \frac{\hat{\mu} - LSL}{3\hat{\sigma}}$	Estimates process capability for specifications that consist of a lower limit only (for example, strength). Assumes process output is approximately normally distributed.
$\hat{C}_{p,upper} = \frac{USL - \hat{\mu}}{3\hat{\sigma}}$	Estimates process capability for specifications that consist of an upper limit only (for example, concentration). Assumes process output is approximately normally distributed.
$\hat{C}_{pk} = \min\left[\frac{USL - \hat{\mu}}{3\hat{\sigma}}, \frac{\hat{\mu} - LSL}{3\hat{\sigma}}\right]$	Estimates what the process is capable of producing, considering that the process mean may not be centered between the specification limits. (If the process mean is not centered, $\hat{C}_p$ overestimates process capability.) $\hat{C}_{pk} < 0$ if the process mean falls outside of the specification limits. Assumes process output is approximately normally distributed.

Figure 4.12: Hole 3 C'Bore True Position – Production Baseline (top) & Enhanced Laser Chassis (bottom)



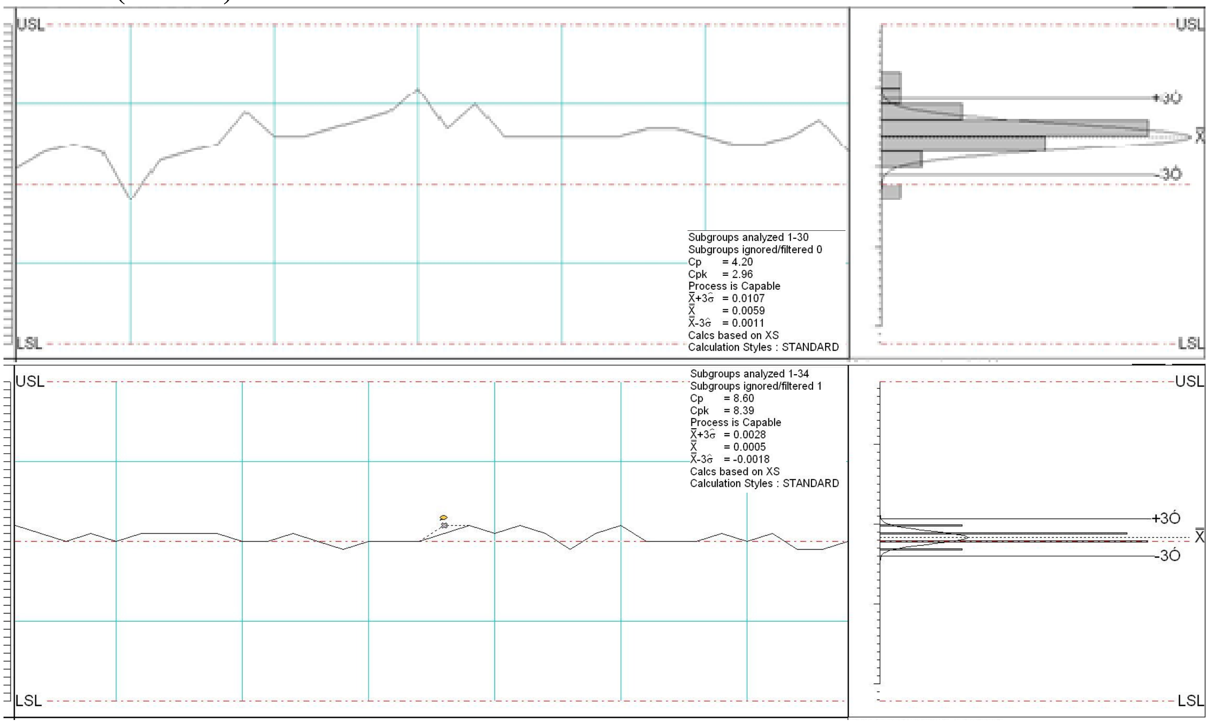
* The yellow data point denotes a part that had mechanical damage caused by a machine in the seat manufacturing process other than the enhanced laser chassis.

Figure 4.13: Hole 3 Spray to C'Bore X – Production Baseline (top) & Enhanced Laser Chassis (bottom)



* The yellow data point denotes a part that had mechanical damage caused by a machine in the seat manufacturing process other than the enhanced laser chassis.

Figure 4.14: Hole 3 Spray to C'Bore Y – Production Baseline (top) & Enhanced Laser Chassis (bottom)



* The yellow data point denotes a part that had mechanical damage caused by a machine in the seat manufacturing process other than the enhanced laser chassis.

Task 3.0 Laser and Scan Head Chassis Development

Subtask 3.1 Laser Chassis Development

Develop an enhanced laser chassis that provides optimum space utilization, user friendly operator interface, in-process gaging, temperature compensation, cover gas and debris management, with precise real-time coordination control between machine motion and laser firing. The deliverable from this effort will be the demonstration and performance testing of the enhanced laser chassis.

The development of the enhanced laser chassis can be broken down into the following key activities: baseline of the current production chassis, mechanical/control concept development, detailed mechanical design, control strategy development, and enhanced laser chassis build.

The current production chassis was baselined with respect to each of the following enhancement attributes: space utilization, cover gas delivery, debris management, in-process gauging, required warm-up time, real-time coordination of motion and laser, and user interface.

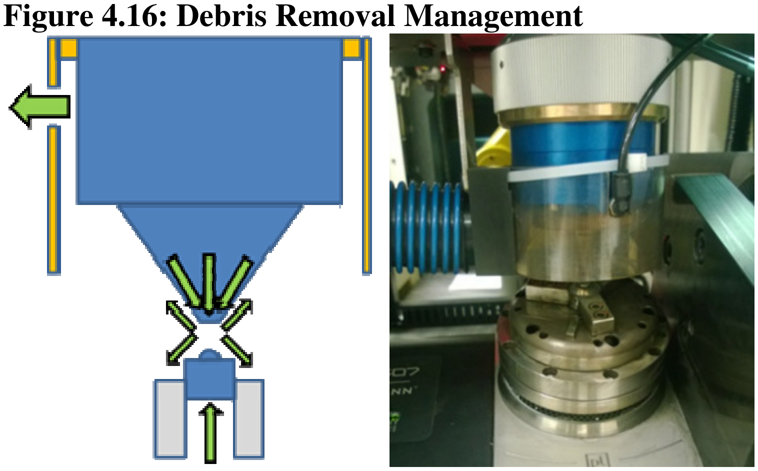
Figure 4.15: Laser Chassis Baseline Summary

ATTRIBUTE	CURRENT BASELINE	GOAL
SPACE UTILIZATION	•UTILITIES INTERFERE WITH AUTOMATION	•ELIMINATE INTERFERENCES WITH AUTOMATION
COVER GAS DELIVERY	•SINGLE GAS INLET, PRODUCTION STOPS WHEN GAS IS LOW	•IMPLEMENT AND DEMONSTRATE REDUNDANT GAS INLET
DEBRIS MANAGEMENT	•INSUFFICIENT FILTER CAPACITY •NO WORK AREA SEGREGATION	•IMPROVE FILTERING •PREVENT DEBRIS FROM REACHING CRITICAL COMPONENTS
IN-PROCESS GAUGING	•PROBE ONLY USED FOR CRASH PREVENTION •CAMERA NOT IMPLEMENTED	•DEVELOP AND DEMONSTRATE PROBE AND CAMERA GAUGING IN SIMULATED PRODUCTION
TEMPERATURE COMPENSATION	•NO TEMPERATURE COMPENSATION •REQUIRES SIGNIFICANT WARM-UP TIME	•REDUCE WARM-UP TIME TO 15 MINUTES
REAL-TIME COORDINATION OF MOTION AND LASER	•NO REAL TIME COORDINATION •JOB SELECTION ADDS CYCLE TIME	•EXTEND FIELD OF VIEW OF SCANNER WITH CORRDINATED MOTION •JOB SELECTION DURING MOVEMENT
USER INTERFACE	•DIFFICULT PROGRAMMING •INTERMITTENT COMMUNICATION FAULTS	•INTUITIVE PROGRAMMING •ROBUST COMMUNICATION

One of the main focuses for mechanical development was to develop a concept to improve robot access for improved part loading. A machine layout concept was developed titled “bridge modification”. This concept, which was selected using a weighted matrix evaluation approach over other concepts, has a reconfigured Z-axis structure (bridge) to allow the machine to be much more accessible for measurement and part loading. This in turn improves key performance categories while maintaining some similarities to the current production chassis and keeps overall risk within acceptable levels.

Another main focus for mechanical development was to develop a concept to improve debris management. The baseline analysis uncovered the need for an effective means for debris removal over-the-part in addition to the through-the-part vacuum currently employed. A concept was developed and prototypes were made to test the concept.

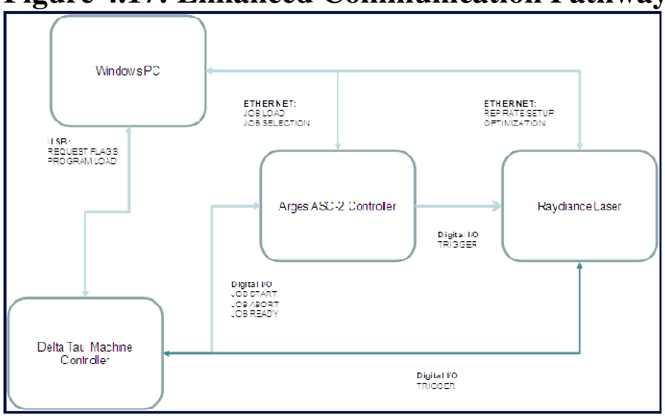
Figure 4.16: Debris Removal Management



Microlution and Delphi documented specific goals for in-process measurement. Programming work was completed to improve the probing and vision capabilities of the machine, including increasing the speed of some of the probing routines on the current production chassis. Using the enhanced laser chassis, a demonstration program was developed to show the capability to measure fuel injector nozzle seats at pre-defined intervals.

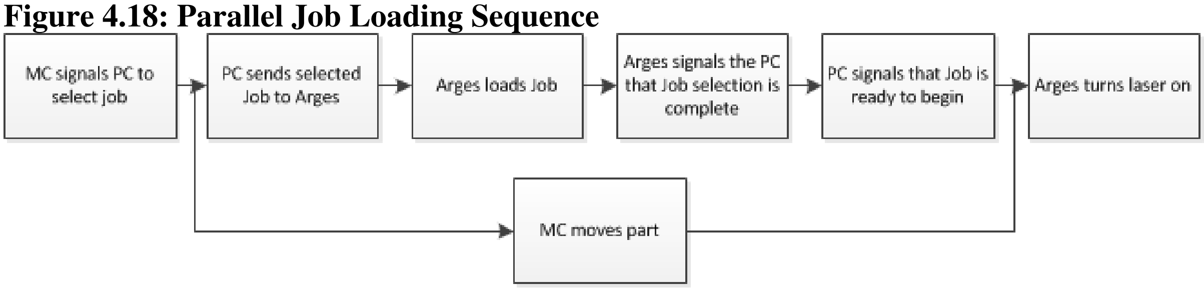
The main focus for control development was to develop concepts to address shortcomings uncovered by the baseline analysis, particularly with regard to coordination of motion, scan head/laser control, and user interface for programming. Enhanced communication architecture allows for real-time coordination and differs from the current one in that an I/O connection was added to enable the machine to directly fire the laser rather than relying on the scan head to fire the laser. A new parallel job loading sequence concept was developed to eliminate the extra cycle time currently caused by job loading. The main difference between this new method and the current method is that the new method allows machine motion to happen during the time required for job loading, thereby reducing the part cycle time by approximately 5%.

Figure 4.17: Enhanced Communication Pathways



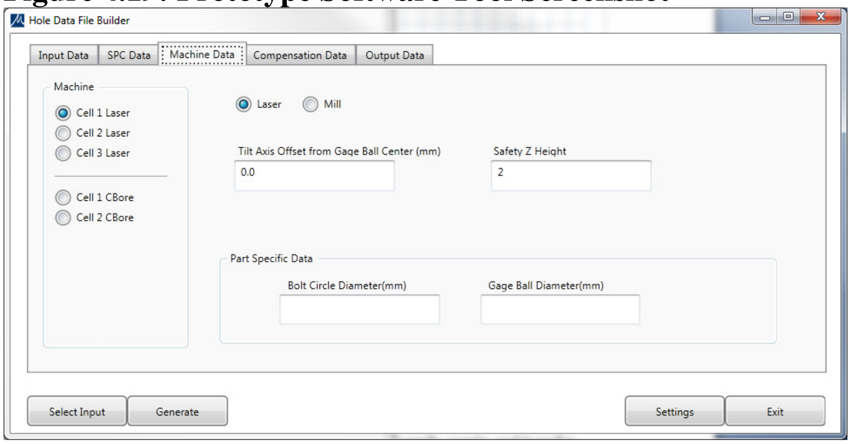
Enchanced Machine Codes		
G/M-Codes	**Description**	**Enhancement**
G144.1	Controls triggering logic of laser	Added ability for machine controller AND/OR Arges controller to trigger laser
G146.1-G146.2	Override of trigger enable	New funtion, enables machine controller to prevent the laser from accepting triggers
G147.1-G147.4	Machine control laser trigger	New function, enables machine controller to trigger laser
G131	Selection of Arges jobs	Enabled simultaneous job selection and machine movement
M144.1-M144.2	Arges triggering mode	New function, enables simultaneous motion and laser firing

Figure 4.18: Parallel Job Loading Sequence



An enhanced user interface concept was developed to streamline the programming of scan head jobs and machine programs. The current production process requires the user to utilize several different software packages, including on-machine software packages, to create and edit programs. The new concept essentially combines the functions of these software packages into one user interface. A new prototype software tool was developed to allow the user to easily create and transfer programs to the machine. This software tool eliminates significant manual data transfer and is a building block for the ability to make complex feature shapes.

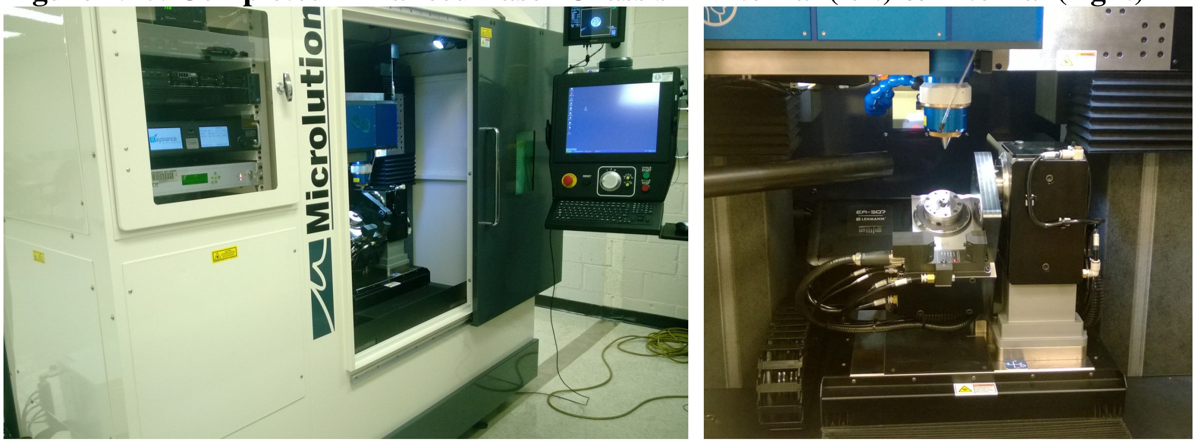
Figure 4.19: Prototype Software Tool Screenshot



One of the main shortcomings of the current production chassis is intermittent communication faults that require the user interface software to be restarted. Microlution researched and performed tests to get to the root causes of these issues. Several specific issues were found and corrected. In addition to these communication faults, several usability improvements were suggested and implemented. Finally, an Arges firmware issue that caused intermittent communication faults was successfully isolated and diagnosed with the help of Delphi and Raydiance. This fault was mitigated so that it no longer causes production stoppages for Delphi.

A high-speed milling spindle, tool sensor, and second user-access door were designed and built into the enhanced laser chassis. As previously described, the milling spindle was added because laser drilling of the counterbores was determined to be non-viable. Its implementation provides improved prototyping capability (new feature geometries, better accuracy between milled and laser machined features, up to 20x faster cycle time for prototypes). The tool sensor enables easy set-up of new milling tools in the spindle. The added user access door provides improved access for tool changing and visibility. In addition to the mechanical and electrical integration of these new items, the machine user interface software was enhanced to provide easy use of spindle and tool sensor functions.

Figure 4.20: Completed Enhanced Laser Chassis – External (left) & Internal (right)



The new mechanical features of the enhanced laser chassis include:

- Redesigned Z-axis for faster motion, enhanced automation access, and more flexibility for sensor integration;
- New scan head mounting design to eliminate thermal errors;
- Addition of milling spindle and tool sensor for combined milling and laser machining capability;
- Addition of access door in rear of enhanced laser chassis for access to spindle and sensors;
- Addition of additional thermal control plate for tilt axis to reduce thermal errors;
- Improved cable and tube routing for easier serviceability;
- Improved separation of laser from processing area;
- Improved interlock for laser access panel and;
- Improved debris removal system.

Standard testing was performed as well as testing focused on the demonstration and performance test of the enhanced laser chassis with 1) a load and unload time to work position in 3.0 seconds or less and 2) capability to synchronize movement during the laser firing sequence (Go/No-Go Decision Point).

Test Conditions and Method of Measurement (Load/Unload Time):

In order to address item 1, Microlution developed a load/unload test station. The goal of this test station was to demonstrate the capability to load and unload fuel injector nozzle seats in less than the 3.0 second target time. The station consists of an HSK chuck that is the same chuck that was initially mounted in the enhanced laser chassis and an articulating arm that can load and unload part holders from the HSK chuck. The articulating arm has two clips at the end of the arm to speed loading – the arm can have a part holder ready to load when it moves to unload the finished part holder. The method of time measurement was to video the action of the load/unload test and machine motions and then analyze the start/finish times during playback.

Test Results and Milestone Verification Data (Load/Unload Time):

Testing was conducted demonstrating a total transfer time of 2.9 seconds, which met the 3.0 second target time. Although the test was conducted using an HSK style chuck (work holding concept initial), this test station would yield the same result if it were modified to accommodate the 1 piece collet – 3 jaw chuck (work holding concept revised) because the fixture size, mass, and required motions to load and unload the 1 piece collet – 3 jaw chuck are very similar to those required for the HSK style chuck.

Figure 4.21: Load/Unload Test Station – CAD Model (left) & Actual (right)

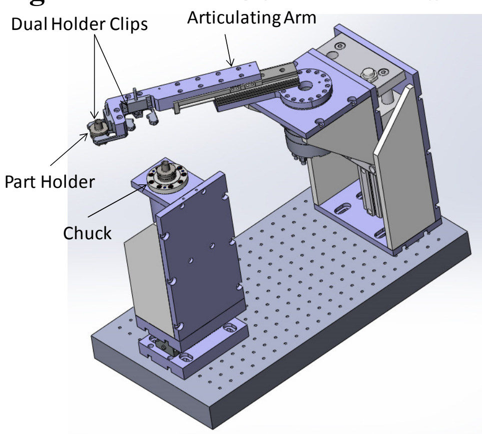


Table 4.5: Demonstrated Part Load/Unload Times

Step	Time (s)
Machine move to unload position	0.75
Part unload/load	1.4
Machine move to process position	0.75
Total	2.9

Test Conditions and Method of Measurement (Movement Synchronization):

Item 2 was achieved by utilizing the enhanced laser communication architecture (additional laser trigger) and developing software features to allow the laser triggering to be synchronized with the machine motion.

Test Results and Milestone Verification Data (Movement Synchronization):

The result of this achievement is the ability to make taper-controlled laser slots with arbitrary 5-axis trajectory. This feature was successfully demonstrated to make prototype fuel injector nozzle seats with “non-standard” flow orifice shapes. Using this feature along with the high-speed milling spindle, the cycle time to make a fuel injector nozzle seat was reduced by 20x, from > 40 minutes to 2 minutes.

Subtask 3.2 Integration and Test
Integrate optimum ultrafast laser system, high performance scanning head, and optimized work holding solution with enhanced laser chassis developed in Subtask 3.1. Target results realized from Tasks 1 and 2 will be applied. Perform system debug and testing to confirm integrated system meets targets of the tasks outlined above.
Milestone 3.2.1 Demonstrate enhanced laser chassis meets or exceeds performance targets.

Standard testing was performed as well as testing focused on the demonstration and testing of the fully integrated ultrafast laser system with 1) warm-up time to stability in < 15 minutes, 2) cleaning of debris from work holding once per 20 hours of continuous operation, and 3) measurement of counterbore depth and diameter at programmable intervals (Go/No-Go Decision Point).

Test Conditions and Method of Measurement (Warm-Up Time to Stability):

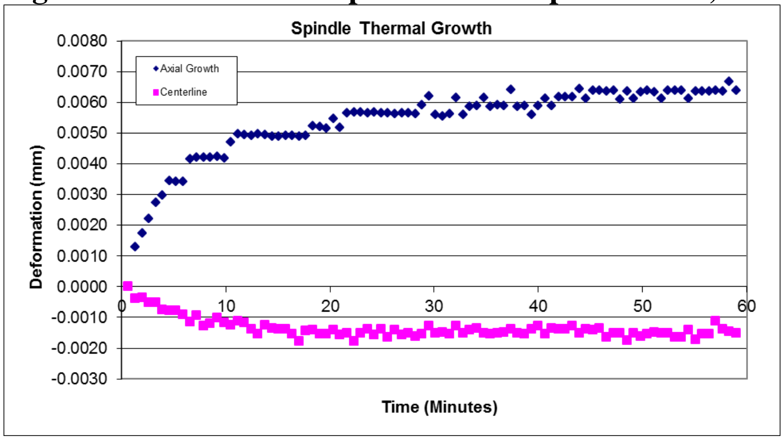
In order to address item 1, thermal characterization work was conducted. The change in drilled hole position over the warm-up period was found to be related primarily to Z-axis growth of the tilt/rotary stage and X-axis growth of the Arges scan head; therefore, these were the areas of focus for the thermal characterization work. In order to evaluate the results, two relevant metrics were defined: total positional change to stability and time to reach a stability level of < 0.005mm from a cold start. The typical cold-start condition was defined as a machine that has been powered on but sits idle for more than 2 hours. The warm-up was found to be strongly tied to temperature rise in the tilt stage and the addition of a temperature-controlled plate and compensation model can effectively reduce the error from this source to below the desired level. Work on the second thermal source, the Arges scan head, was focused on redesigning the mount for the head. The new mount design constrains the Arges scan head near the laser output, effectively eliminating thermal errors associated with head warm-up.

The test method for the Z-axis deviation of the tilt stage was to measure the displacement of a spherical artifact mounted to the tilt/rotary stage (in the position of a part) using a Lion Precision capacitive sensor during normal operation conditions. The method for the Arges scan head stability test was to measure the displacement of the laser aperture nozzle in the X-axis direction using a Mitutoyo precision test indicator during normal operating conditions.

Test Results and Milestone Verification Data (Warm-Up Time to Stability):

Initial testing was conducted that showed a significant reduction in warm-up time, from > 30 minutes with the original design to < 15 minutes with the enhanced laser chassis – meeting the warm-up time target. Further testing completed in Subtask 2.2 showed that no warm-up was necessary as the capability run was started after the enhanced laser chassis had been idle for over 2 hours.

Figure 4.22: Thermal Displacement of Spindle at 80,000 rpm



Test Conditions and Method of Measurement (Debris Cleaning):

The criteria of the cleanliness is the duration of time the Delphi production machines can be run without negative effects to part clamping and part quality due to debris. Part and collet fixturing problems occur as laser debris accumulates. Preventative maintenance, including cleaning, is determined by these failures.

Work on improving debris cleaning was focused in two areas: creating better exhaust dynamics near the machining zone and reducing the amount of debris generated on top of the part. To create better exhaust dynamics, a hood was developed that partially encloses the working area while still allowing 5-axis motion. This hood was then connected to an improved vacuum source (Fumex laser fume extractor) and installed on a production machine.

Test Results and Milestone Verification Data (Debris Cleaning):

The system initially allowed Delphi to run production with 20 hours of continuous operation in between fixture cleanings. However, achieving higher metal removal rates adversely affected the ability to meet the > 20 hour debris cleaning target. Additional actions were evaluated to countermeasure this, including varying cover gas pressure/flow, cover gas flow direction, and cover gas ionization.

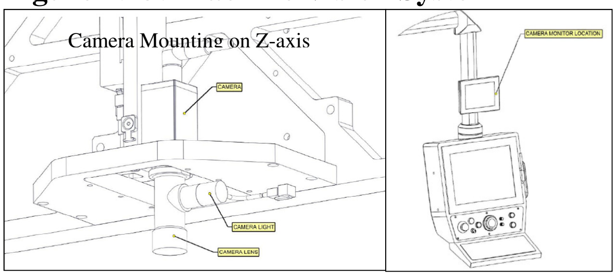
Test results from 19 trial runs of 5 parts each showed a high correlation between debris patterns and cover gas pressure and flow direction. Lower gas pressure and forward cover gas flow resulted in lower debris generation in the counterbores and on top of the part, which are desirable to improve fixture cleaning intervals. High cover gas pressure led to observable debris being spread farther out on the diameter of the part, which would lead to more debris reaching the fixturing. Reverse cover gas flow was theorized to direct the debris upward into the exhaust hood; however, testing showed that a majority of the debris was caught in the counterbore of the part, which is highly undesirable. Finally, cover gas ionization, which was theorized to reduce the tendency of particles to stick to nearby surfaces, showed no discernable effect.

The process variations that showed promise for debris reduction had some effect on proprietary hole geometry. This change in hole geometry requires significant additional work to qualify the new process parameters for production. Delphi must confirm that the change in this hole geometry results in acceptable overall product quality as well as improved debris management. Further testing is planned for Budget Period 2.

Test Conditions and Method of Measurement (Measurement at Programmable Intervals):

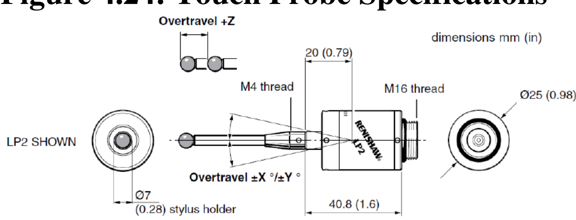
Item 3 was achieved by developing a demonstration part program that measures positions of machined counterbores at programmable intervals. The program enables the user to define which features are measured, the measurement interval, and if multiple measurements are taken per measurement interval.

Figure 4.23: Machine Vision System



Camera and Lens Specifications	
Camera/Controller	H200M/XG-7502
Camera Resolution	2MP (1600x1200), monochrome
Image processor	High Speed DSP
Image Processing	Numerous processing algorithms and vision tools, including image enhancement filters, edge detection, character recognition, etc.
Communication	TCP/IP communication with Microlution PC for data capture
Lens	Moritex MML8-40D (6x magnification) telecentric lens
Lighting	Coaxial light through lens (red), controllable intensity

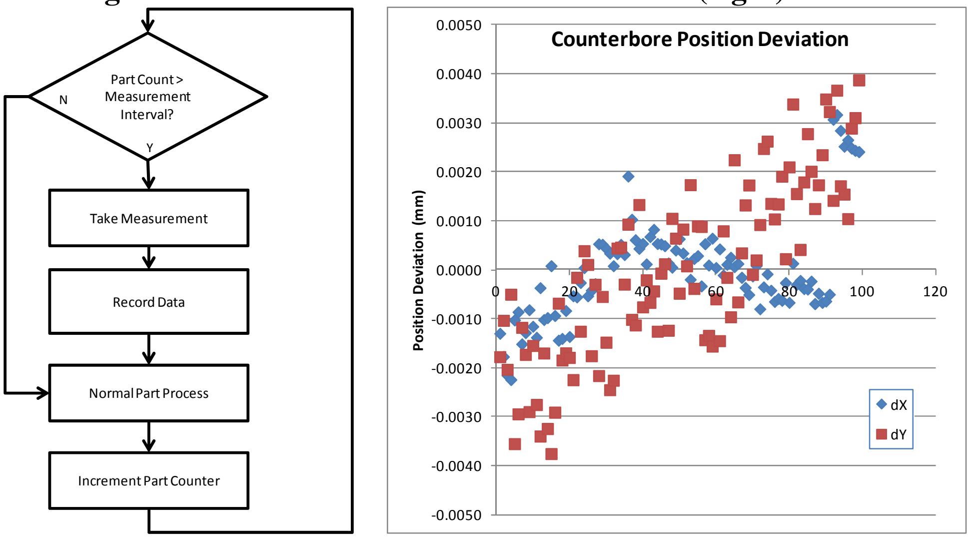
Figure 4.24: Touch Probe Specifications



Specification	Value
Probing directions	±X, ±Y, +Z
Stylus overtravel in X and Y	±12.5°
Stylus overtravel in Z	6.5mm (0.26 in)
Trigger force in X and Y*	0.7N (0.16 lbf)
Trigger force in Z*	5.8N (1.3 lbf)
Unidirectional repeatability with 35mm stylus	1.0µm (0.00004 in) for test velocity of 480mm/min (1.5 ft/min)
Sealing	IP X8
Stylus	TM2-0310-BC (Q-Mark); alternate styli available up to 100mm long

Test Results and Milestone Verification Data (Measurement at Programmable Intervals):

Figure 4.25: In-Process Measurement Programming Flow Chart (left) & Sample Data Showing Position Variation of a Machined C'Bore (right)



Functional tests were performed to demonstrate the following new capabilities of the enhanced laser chassis:

- Simultaneous 5-axis milling: For this test, a 5-axis part program was generated using Cimitron computer aided manufacturing (CAM) software and successfully run on the enhanced laser chassis to mill non-circular counterbores into a fuel injector nozzle seat.
- Laser firing coordinated with machine motion: For this test, a non-circular laser feature was successfully programmed and machined into a fuel injector nozzle seat. To achieve this feature, the laser triggering was coordinated with the path of the feature.

<u>Task 4.0 Optimization and Valve Seat Build</u>

Subtask 4.1 Integrated Component Processing

Optimize process parameters to produce fuel injector valve orifice nozzle spray holes and counterbores using fully integrated and tested enhanced laser system.

During the last week of September 2013, the enhanced laser chassis acceptance testing was performed and the chassis shipped to Delphi. In October 2013, the enhanced laser chassis was installed and debugged at Delphi. 10W laser process parameters were then optimized by producing spray holes in sheet metal as it is much faster to make holes and analyze hole geometry in sheet metal compared to real parts. Based on the learnings in Subtask 1.3, counterbores were produced using the high-speed milling spindle that was added to the enhanced laser chassis.

The desired hole geometry is one that is straight and cylindrical with a small taper that gets bigger as you travel deeper into the drilling direction (negative taper). Sharp entrance and exit conditions are also desirable hole conditions. A large “trumpet” shape at the entrance of the hole, positive taper, a barrel shape or other deviations from straight, and “serrations” on the hole entrance along the walls are unfavorable hole conditions.

Test Conditions and Method of Measurement:

To achieve optimized 10W laser process parameters for spray hole production, experiments were conducted in 0.203mm thick sheet metal. The existing production 10W algorithm was used as a starting point (baseline). Spray holes are produced in multiple process steps. Laser process parameters were dialed in to produce the desired pilot hole (initial process steps) and then further adjusted to produce the desired overall spray hole (final process steps). Focus and attack angle were the primary process parameters that were adjusted thru the multiple iterations of spray holes produced. After each iteration, hole characteristics (i.e. taper, trumpet) were evaluated using an Alicona InfiniteFocus (form and roughness measurement system) until a desired spray hole was produced.

Test Results and Milestone Verification Data:

With optimized process parameters, a straight shape with no barrel or hooks was produced. The large trumpet effect documented in the initial spray hole iteration was nearly eliminated, there was no evidence of serrations near the hole entrance, and predictable taper control was realized.

Figure 4.26: Spray Hole Pilot – Initial (left) & Final (right)

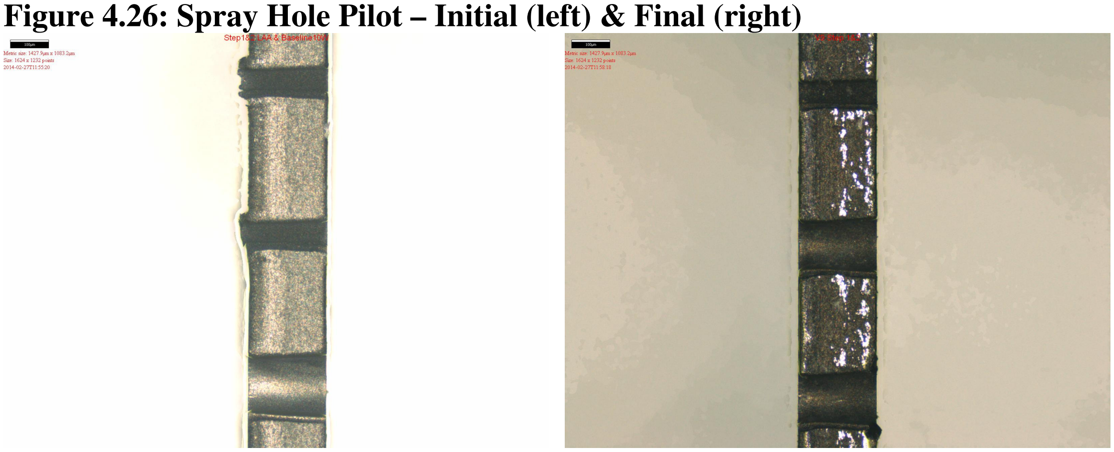
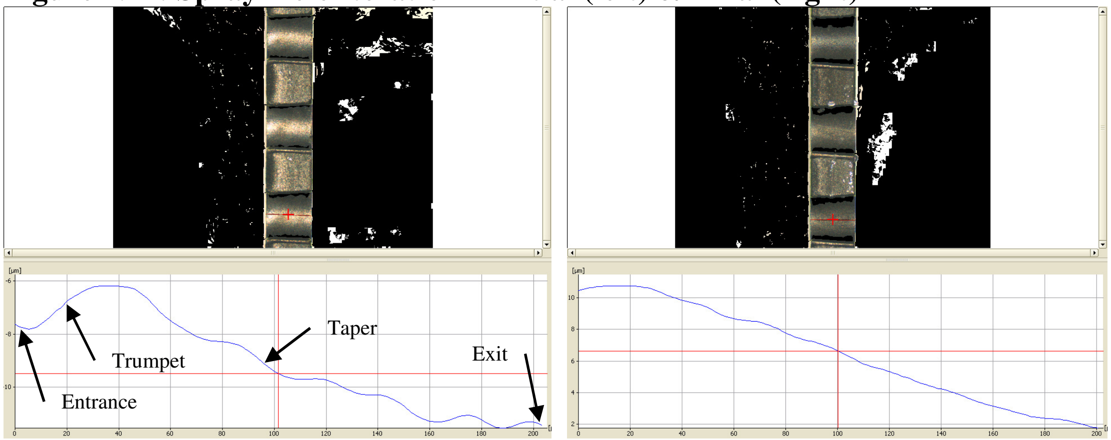
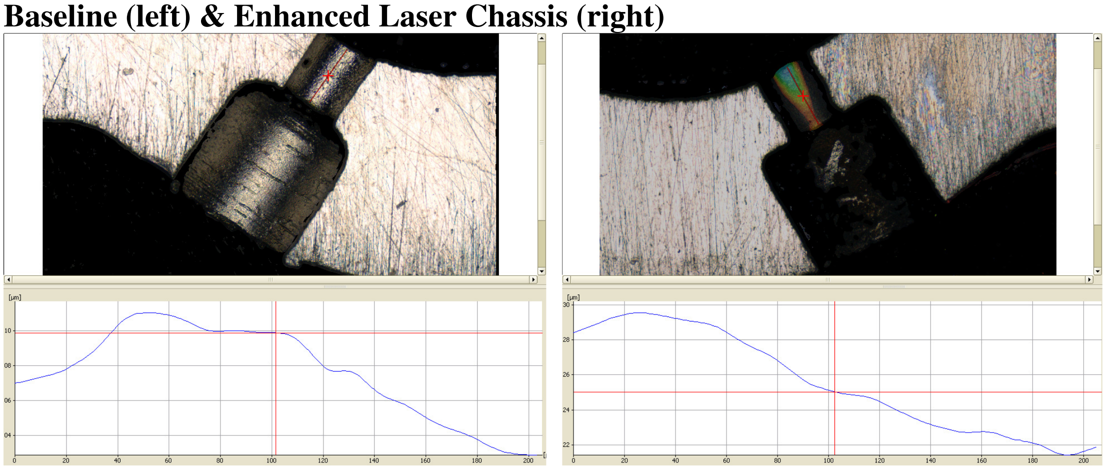


Figure 4.27: Spray Hole Iteration – Initial (left) & Final (right)



Once an optimized set of process parameters was achieved in sheet metal using the enhanced laser chassis, the optimized algorithm was used to manufacture spray holes and counterbores in a fuel injector nozzle seat blank. A generic, symmetric spray hole pattern was used. The optimized algorithm from the sheet metal development resulted in a nearly identical result with very little "fine tuning." This is not typical, but a result of the new platform improvements and set-up techniques developed.

Figure 4.28: Spray Hole & C'Bore in Fuel Injector Nozzle Seat Blank – Production Baseline (left) & Enhanced Laser Chassis (right)



Subtask 4.2 Develop Valve Seat

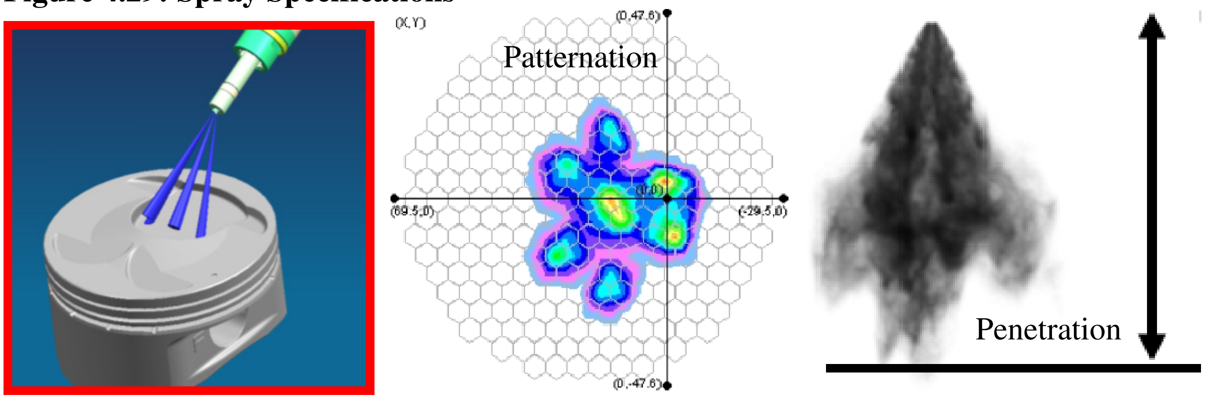
Develop fuel injector valve seat configurations to fulfill customer specific product application requirements using the product development flowchart identified as Figure 11 in project submission.

Milestone 4.2.1 Utilize enhanced laser chassis to develop a seat for a specific customer application.

Delphi established a cross functional team to focus on fuel injector nozzle seat development using enhanced laser drill capabilities. Initial studies were performed to characterize fuel injector nozzle seat flow hole geometry and baseline the effects on performance. Initial product and process designs were completed and developed. Production intent fuel injector nozzle seats were produced to establish and validate the measurement system. Gauge R&R studies were performed, results reviewed, and measurement capability was established.

Spray specifications include injector flow rate (supply pressure), pattern (number of plumes, centroid locations and/or spray and bend angles, plume diameters, plume-to-plume mass distribution), and penetration.

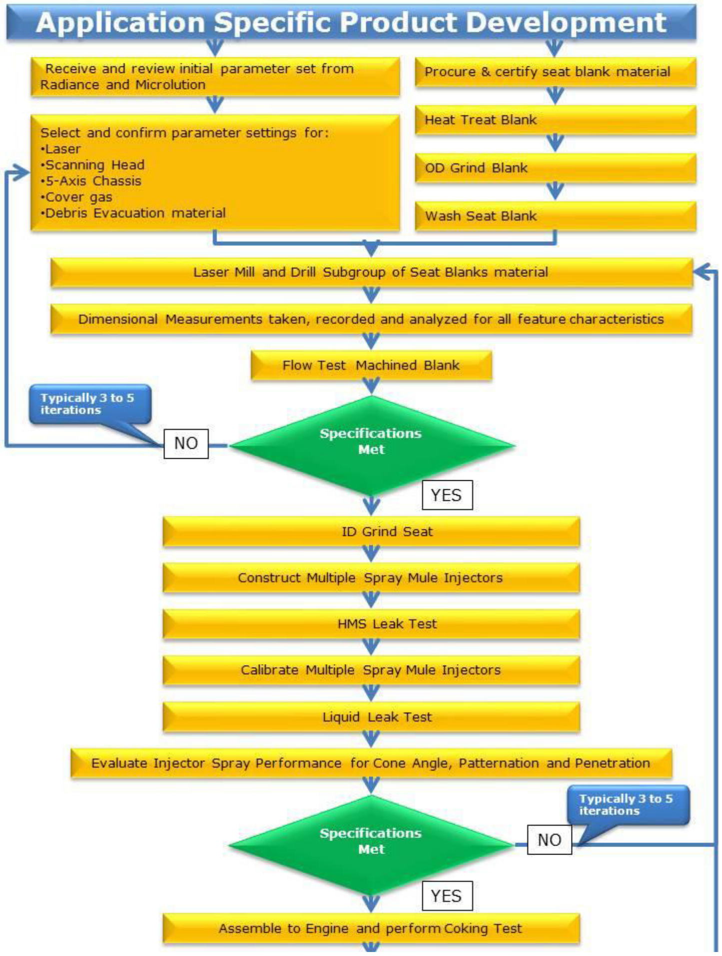
Figure 4.29: Spray Specifications



Test Conditions and Method of Measurement:

Customer specific fuel injector nozzle seats for "Customer X" were produced on the enhanced laser chassis with optimized process parameters using the product development flowchart (Figure 4.30).

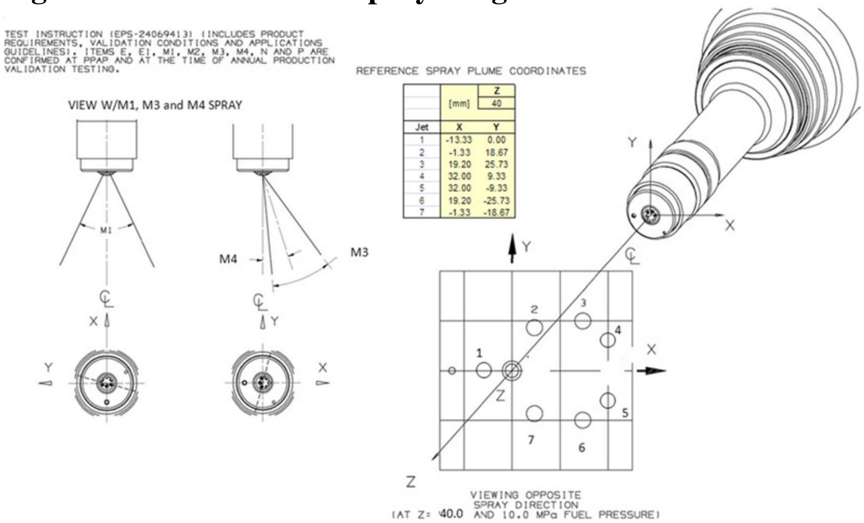
Figure 4.30: Product Development Flowchart (Figure 11 in Project Submission)



The primary objective of the development effort was to achieve the following static flow, penetration, and spray targeting as defined by Customer X:

- Static Flow: 9.90g/s ± 3%
- Penetration: < 68mm
- Spray Targets: Shown in Figure 4.31

Figure 4.31: Customer X Spray Targets



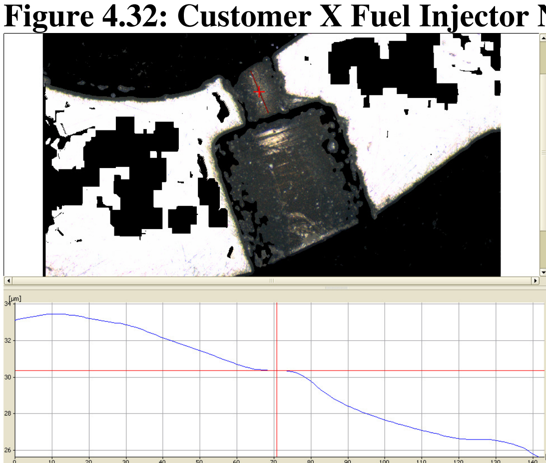
	[mm]	Z
		40
Jet	X	Y
1	-13.33	0.00
2	-1.33	18.67
3	19.20	25.73
4	32.00	9.33
5	32.00	-9.33
6	19.20	-25.73
7	-1.33	-18.67

Test Results and Milestone Verification Data:

Valve seat geometry and performance was optimized using multiple iterations of fabrication through all process segments, extensive measurement, functional testing, and overall analysis.

Using the specific specifications supplied by Customer X, the fuel injector nozzle seat blank was set-up and run on the enhanced laser chassis. Layouts from the Werth CMM and the profile measurement completed on the Alicona InfiniteFocus confirmed that the part conformed to the desired specifications. Minimal fine tuning was required, as the new enhanced laser chassis techniques and algorithms worked as designed.

Figure 4.32: Customer X Fuel Injector Nozzle Seat



The fuel injector nozzle seats were then assembled into spray mules to complete the analysis. The results show that fuel injector nozzle seats developed for Customer X using the enhanced laser chassis with optimized process parameters meet all customer specifications.

Table 4.6: Static Flow Results
Specification: 9.90g/s ± 3%
Result: Average within 2% of requirement

Injector S/N	stroke	10 mpa
301	60	9.39
303	58	9.73
304	60	10.04
	59.3	9.72
		-1.83%

Table 4.7: Penetration Results
Specification: < 68mm
Result: Average = 60mm

S/N	Penetration (mm)			
	Average	StDev	Max	Min
BH57-301_Z	61.2	1.9	64.5	57.2
BH57-303_Z	60.2	1.5	62.7	56.7
BH57-304_Z	59.3	1.3	61.7	57.1
Overall Average	***60.2***	*n/a*	***62.9***	***57.0***
StDev	*0.9*	*n/a*	*1.4*	*0.3*
Max	*61.2*	*1.9*	*64.5*	*57.2*
Min	59.3	*1.3*	*61.7*	*56.7*
Range	*1.8*	*0.6*	*2.8*	*0.5*

S/N	Penetration (mm)			
	Average	StDev	Max	Min
BH57-301_N	60.5	1.7	64.6	57.3
BH57-303_N	60.4	1.6	63.8	56.8
BH57-304_N	59.1	2.1	64.8	55.7
Overall Average	***60.0***	*n/a*	***64.4***	***56.6***
StDev	*0.8*	*n/a*	*0.5*	*0.8*
Max	*60.5*	*2.1*	*64.8*	*57.3*
Min	59.1	*1.6*	*63.8*	*55.7*
Range	*1.4*	*0.5*	*1.0*	*1.6*

* Analysis based on SAE standard J2715; Statistics for each S/N from 30 images.

Figure 4.33: Spray Targeting Results

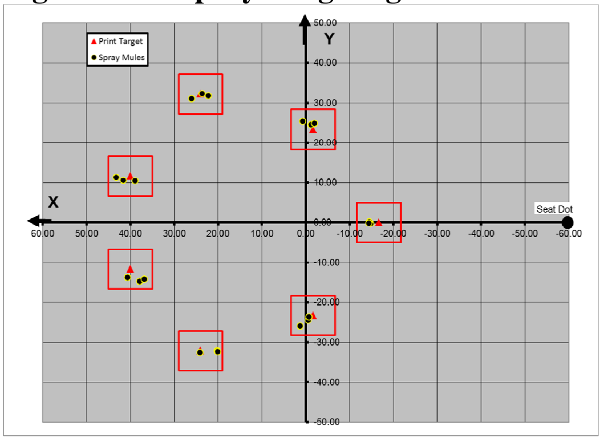


Figure 4.34: Hexcell Footprints of S/N 301, 303, 304 (left to right)

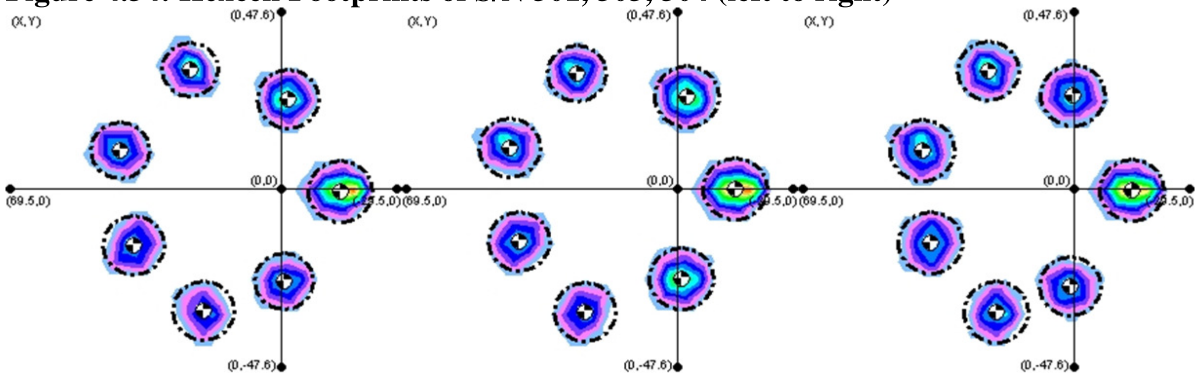


Figure 4.35: Spray Imaging Views Definitions

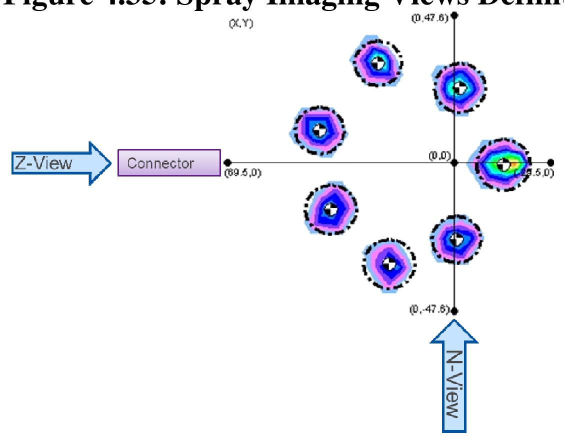


Figure 4.36: Spray Imaging – Single Shadowgraph of S/N 301, 303, 304 (left to right)

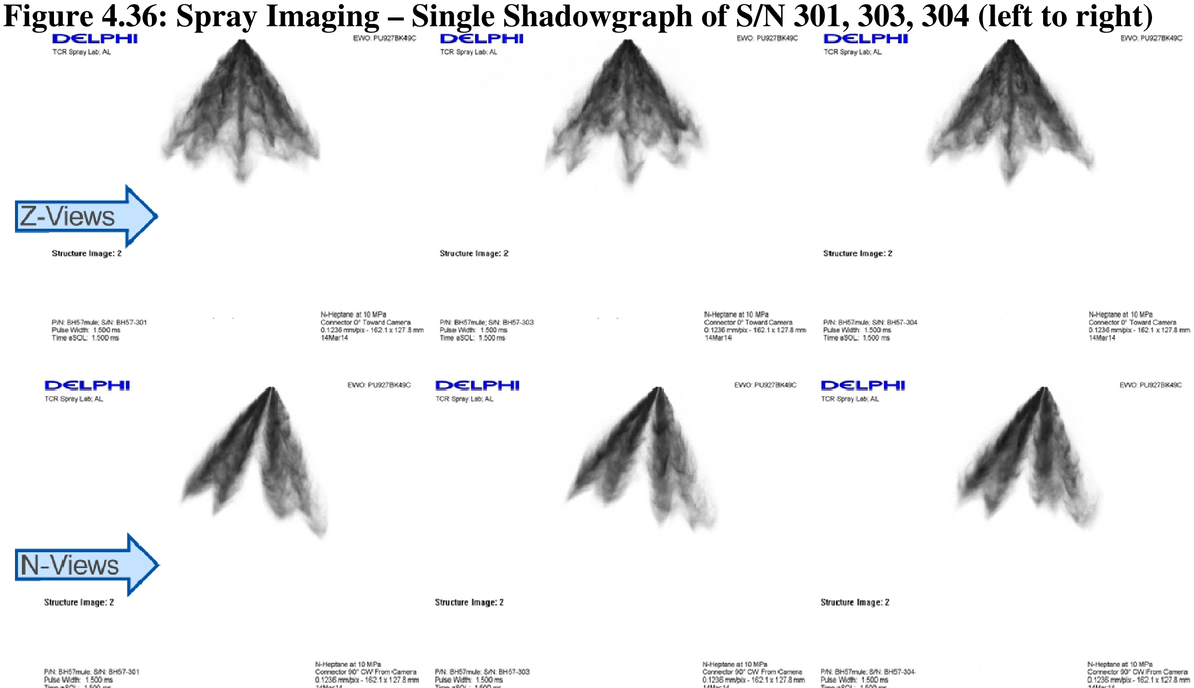
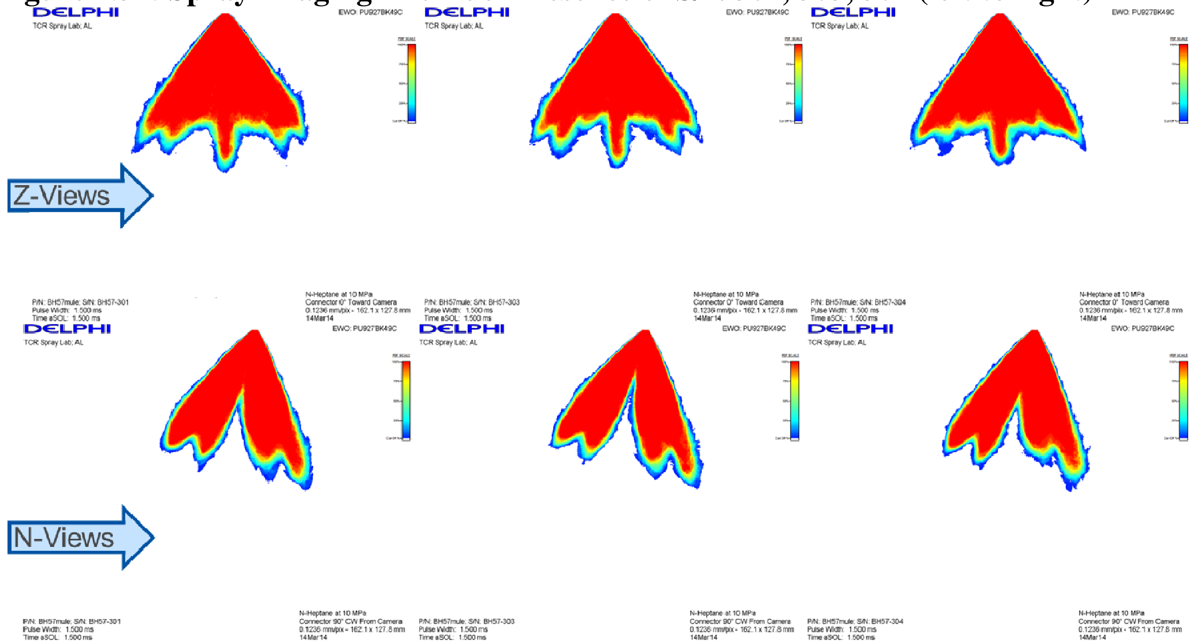


Figure 4.37: Spray Imaging – % Fuel Presence of S/N 301, 303, 304 (left to right)



At the project onset, the goal in Budget Period 1 was to develop an ultrafast laser micromachining platform capable of laser drilling spray holes as well as counterbores in production fuel injector nozzle seat material (heat treated 440A stainless steel). Through the counterbore development effort that took place in Subtask 1.3, it was determined that a 100% laser drilled fuel injector nozzle seat was not a viable solution for Delphi. High-speed milling of the counterbore was chosen as an alternative to laser drilling while spray holes were still procured using laser drilling. While the specific goal of 100% laser drilling was determined to be non-viable for Delphi's application of fuel injector nozzle seats, the alternative approach of integrating high-speed milling into the enhanced laser chassis under development in this project has led to an excellent alternative. Combining these operations on a single hybrid enhanced laser chassis offers a fast, high precision manufacturing method that provides substantial reduction in cycle time and energy consumption compared to the baseline method and has shown to produce parts meeting Delphi's established performance targets and product quality characteristics.

<u>BUDGET PERIOD 2</u> (Task 5.0 – Task 8.0)

<u>Task 5.0 Multi-Application Testbed Development</u>

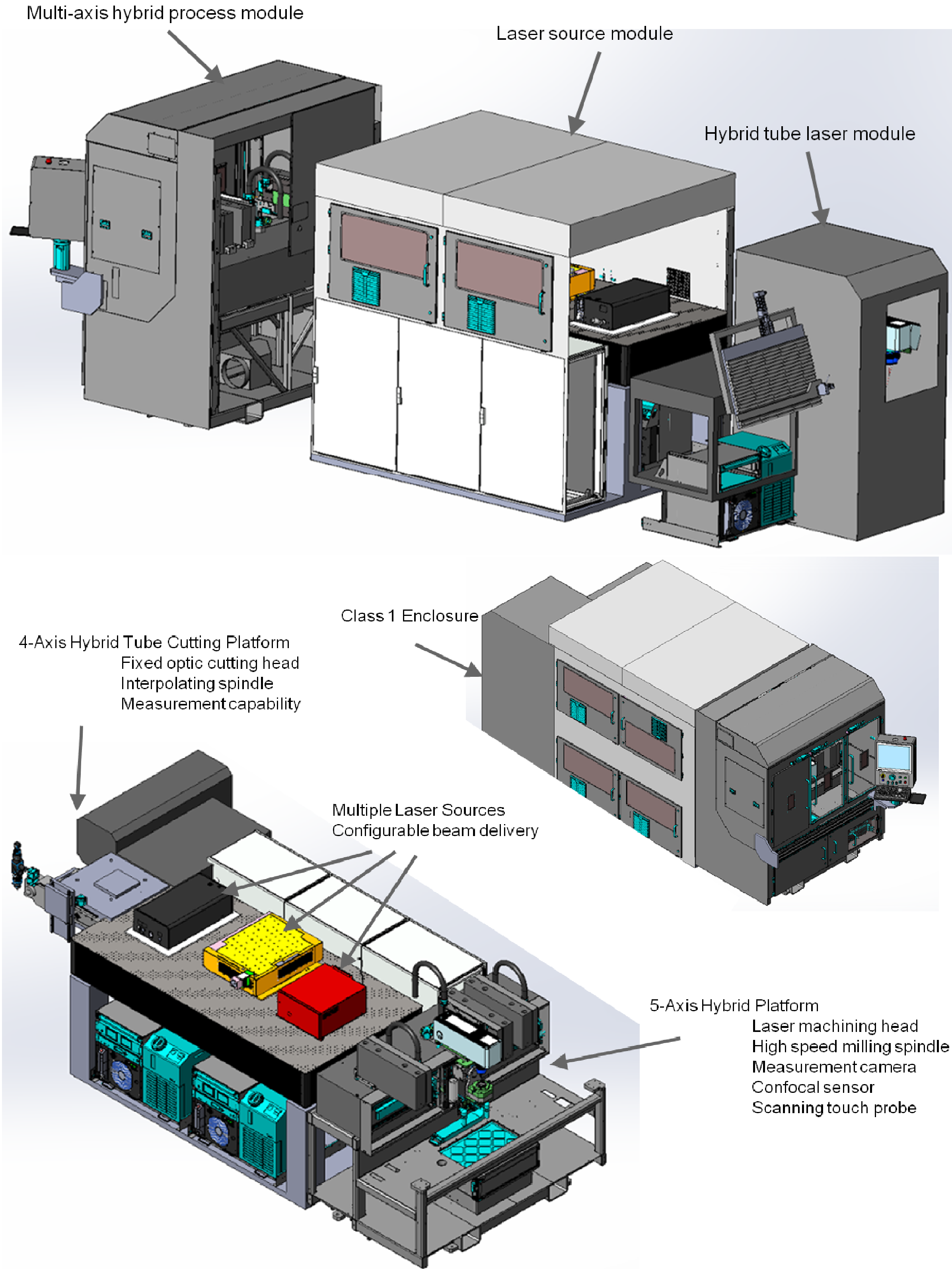
Subtask 5.1 Design Multi-Application Testbed
Design a testbed system that provides an application platform to be used to develop and prove production processes for the identified applications.
Milestone 5.1.1 Demonstrate testbed design meets or exceeds performance criteria
The SMART milestone for this subtask is to develop a testbed design that meets the measurable criteria listed below.

- *Workholding capability*
  - *Cylindrical parts up to 10mm in diameter and 20mm long*
  - *Tubes with 1-6mm diameter, up to 1m long*
  - *Flat disc parts up to 300mm diameter and 10mm thick*
- *Motion capability*
  - *5-axis motion: 25mm X/Y, 40mm Z, 45° tilt, 360° rotation*
  - *Tube cutting motion: 200mm axial, 25mm focus, 360° rotation*
  - *Flat disc parts: ability to reach features on 300mm diameter disc*
- *Accuracy – linear stage accuracy of +/- 1 micron*
- *Processing / measurement capabilities*
  - *Femtosecond laser processing*
  - *Mechanical milling/drilling using 0.1-6mm diameter tools*
  - *Vision measurement of features < 0.5mm in size with measurement accuracy better than 10 microns*
  - *Depth measurement of features with accuracy better than 10 microns*
  - *Tube diameter measurement of tubes 1-6mm diameter with measurement accuracy better than 5 microns*
  - *Tube thickness measurement of tubes 0.1-1mm thick with measurement accuracy better than 10 microns*

The multi-application testbed is comprised of the following three main components (shown in Figure 4.38):

1) The Multi-Axis Hybrid Processing (MAxHP) module to address the needs of Subtasks 6.1, 7.1, 7.2, and 8.2;
2) The Hybrid Laser Tube Processing (HLTP) module to address the needs of Subtask 8.1, and;
3) The Shared Laser Source (SLS) area to supply the laser light to the two processing modules.

Figure 4.38: Multi-Application Testbed Design

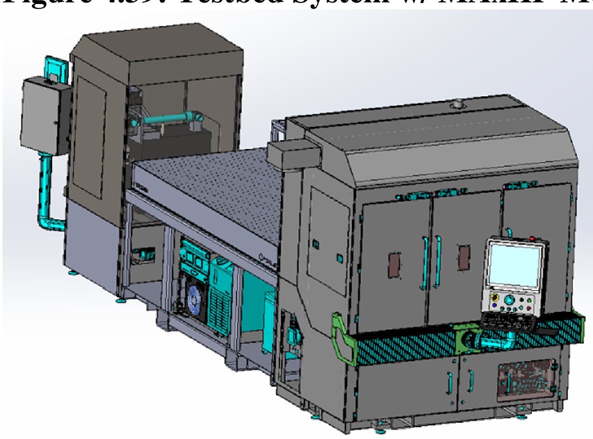


The following sections of this subtask will describe the development & design of each of the three main portions of the testbed.

1) MAxHP Module

The first portion of the testbed is the MAxHP module. Figure 4.39 shows the testbed system with the MAxHP module towards the front of the image. As depicted, the MAxHP module enclosure and user interface is designed to support the three processing capabilities inside the module. The three front doors on the module allow the operator to access each of the measurement, laser cutting, and mechanical cutting systems inside the MAxHP module. Similarly, the user interface is mounted to a sliding track that allows the operator to position the interface panel directly in front of each of the sections of the module.

Figure 4.39: Testbed System w/ MAxHP Module (shown towards the front)



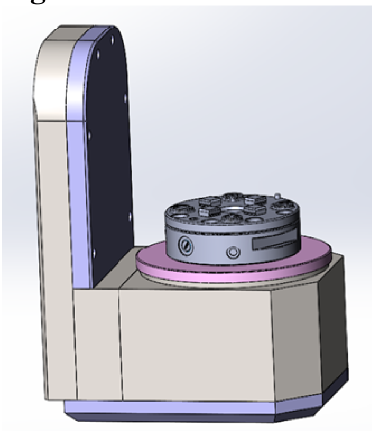
The processing systems inside of the MAxHP module include a measurement station, ultrafast laser cutting station, mechanical milling station, and precision part holding and positioning stages. As planned, the components and system design of the MAxHP module provides the capabilities as described in the SMART milestone for this subtask.

A special rotary stage was developed to support the functionality in the MAxHP module. The rotary stage for this system needs to support the following challenges (requirements) presented by the hybrid processing capability:

a) Accuracy and repeatability required by micromachining applications;
b) Long-term thermal stability required for serial production environments;
c) Dynamic positioning accuracy for laser cutting with motion synchronized between the laser scanner and the motion stages;
d) Fast point-to-point positioning for serial production productivity;
e) Torque requirements driven by cutting forces encountered during mechanical milling;
f) Debris management for both laser-ablation particles and mechanical milling swarf;
g) Fixturing capability to support the range of parts to be processed.

The rotary stage, shown in Figure 4.40, supports these requirements with the combination of the direct-drive motor/encoder unit (requirements a, c, d, and e), its mechanical packaging design including thermal management (requirements b and f) and its integrated fixture chuck system (requirement g).

Figure 4.40: MAxHP Module Rotary Stage



2) HLTP Module

The second portion of the testbed is the HLTP module. This module, shown in Figure 4.41 with the enclosure and user interface, provides processing capability for tube cutting with integrated, in-situ measurement capabilities. As planned, the components and system design of the HLTP module provides the capabilities as described in the SMART milestone for this subtask.

Figure 4.41: Testbed System w/ HLTP Module (shown towards the front)

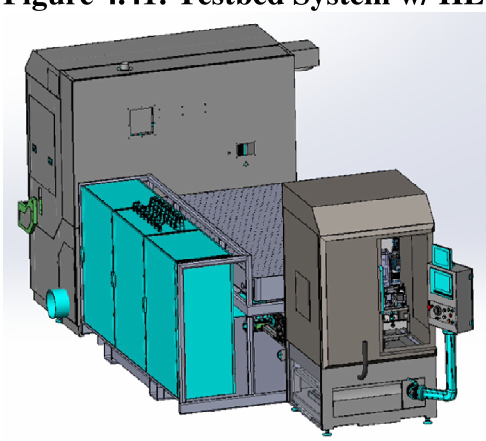
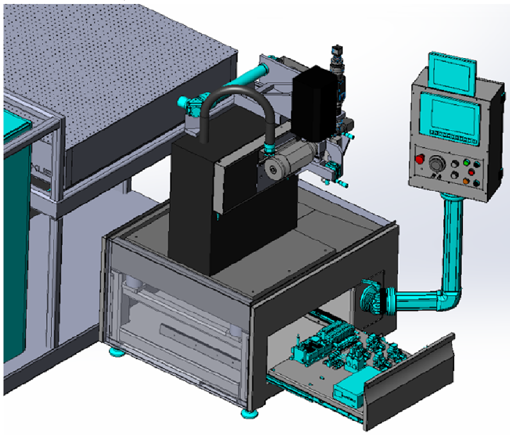


Figure 4.42 shows the HLTP module with the enclosure removed. In Figure 4.42, the configuration of the system base structure, HMI, and electronics drawer are shown. The processing zone inside of the HLTP module includes the measurement sensors, ultrafast laser cutting head, and precision part positioning system. As planned, the components and system design of the HLTP module provides the capabilities as described in the SMART milestone for this subtask.

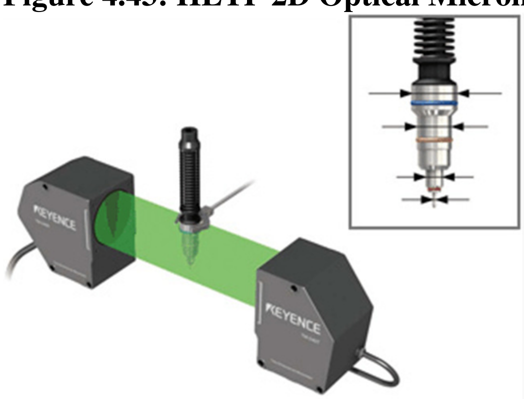
Figure 4.42: HLTP Module (shown w/ enclosure removed and electronics drawer extended)



Test Conditions and Method of Measurement (HLTP Module):

The most critical aspect of the module is the measurement system. Evaluation work was performed to select and validate the components for the measurement system in the HLTP module. Testing was performed to validate the measurement capabilities of the proposed measurement module for the HLTP system. The initial concept for this module consists of two sensors to measure in process outer diameter (OD), inner diameter (ID), and length of the tubing. A 2D optical laser micrometer made by Keyence was chosen to measure both the OD and length of the tubing. The detailed specifications for this sensor are shown in Figure 4.43.

Figure 4.43: HLTP 2D Optical Micrometer



Model	TM-006
Measuring Range	6mm (0.24”)
Smallest Detectable Target	0.04mm (0.001”)
Transmitter/Receiver Distance	60mm (2.36”)
Light Source	GaN Green LED
Measurement Accuracy	+/- 0.5µm (+/- 0.00002”)
Repeatability	+/- 0.06µm (+/- 0.000002”)
Trigger Interval	5.5ms
Enclosure Rating	IP64
Operating Temperature Range	0 to 50°C (32 to 122°F)
Operating Ambient Humidity	35 to 85% non-condensing
Material	Aluminum

The second sensor selected for the measurement module was an industrial image processing sensor to measure the wall thickness of the tube. With the OD measured by the 2D optical laser micrometer, the ID can be calculated by: ID = OD – (wall thickness * 2).

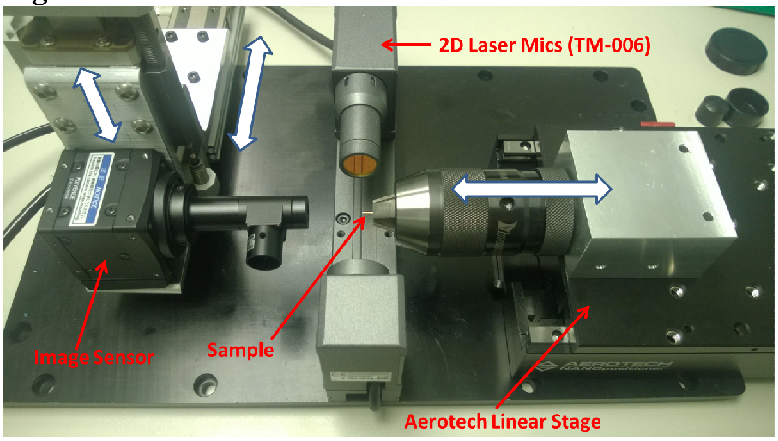
Several different image sensors were evaluated for this function. The primary difference between the sensors that were tested is resolution. Higher resolution is directly related to higher cost of the sensor element and increased image processing time. Therefore, the goal of the testing was to find the lowest resolution sensor that could still deliver the repeatability specified by the process performance capabilities detailed in Milestone 5.1.1. A comparison of the sensors that were tested can be seen in Figure 4.44.

Figure 4.44: HLTP Optical Camera Options

Model	XG-200C	XG-500C	CA-H2100M
Image Pickup Device	1/1.8-inch color CCD	2/3-inch color CCD	1.33-inch color CMOS
Resolution	1,920,000 pixels 1600 (H) x 1200 (V)	4,990,000 pixels 2432 (H) x 2050 (V)	21,000,000 pixels 5104 (H) x 4092 (V)
Pixel Size	4.4µm x 4.4µm	3.45µm x 3.45µm	4.4µm x 4.4µm

A test bench was constructed to replicate the design concept as planned for the HLTP system. The workpiece under measurement was held in a Jacobs-style chuck that was attached to an Aerotech linear stage. The stage allowed the workpiece to be moved in the horizontal direction so that it could be presented to the sensors and then moved away between measurements. The sensors were arranged on the test bench in the same configuration as the design for the HLTP system. The 2D optical laser micrometer was configured so that the tube passes horizontally through the sensor. The camera was positioned to view the end of the tube. Under the camera were two linear pneumatic actuators to allow for fine adjustment of the position of the camera so that it could be aligned to view the wall of the tube. An image of the test bench is shown in Figure 4.45.

Figure 4.45: HLTP Sensor Test Bench



The repeatability requirement for each sensor was derived from the tolerance specifications for the process. It is desirable for the error contribution of the measurement device to be <10% of the total tolerance band for the process. Also, the process capability level target was 5σ (1.667 Cpk) for the purposes of evaluating the sensors. A sample of 30 measurements was taken for each sensor to evaluate the repeatability capability of each sensor. The tube was moved out of the sensor's field of view after each measurement and then returned to the exact same position for the next measurement using the Aerotech linear stage. A 6x telecentric lens was used on all three cameras for the testing. Table 4.8 shows the repeatability target for each measurement type evaluated.

Table 4.8: HLTP Measurement Capability Requirements

Measurement	Sensor Used	Process Tolerance	5σ Repeatability Target
Length	2D laser mics	10µm	1.0µm
OD	2D laser mics	5µm	0.5µm
Wall Thickness	Camera	10µm	1.0µm

Test Results and Milestone Verification Data (HLTP Module):

Graphical representations of the results of the measurements from each of the sensors are shown in Figure 4.46 and a summary table is shown in Table 4.9.

Figure 4.46: HLTP Sensor Capability Data

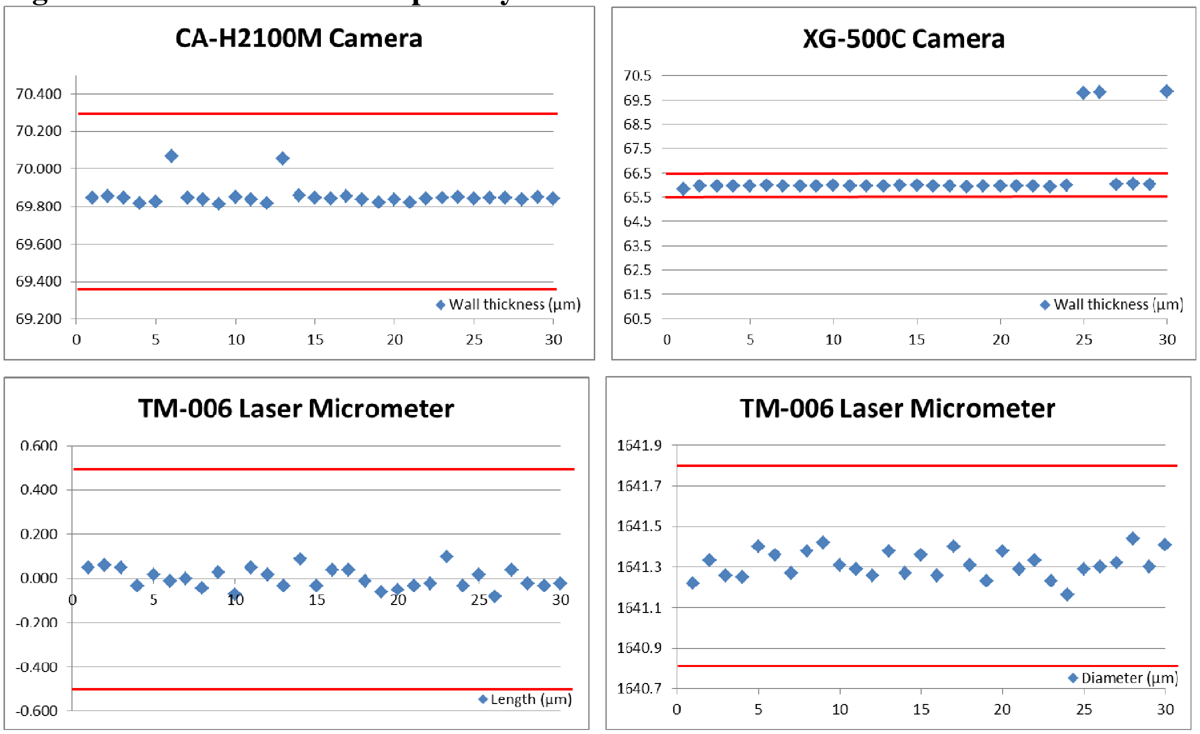


Table 4.9: HLTP Sensor Capability Results

Measurement	Sensor	5σ Repeatability Target	5σ Measured Repeatability
Length	TM-006	1.0µm	0.23µm
OD	TM-006	0.5µm	0.34µm
Wall Thickness	CA-H2100M	1.0µm	0.29µm
Wall Thickness	XG-500C	1.0µm	5.90µm
Wall Thickness	XG-200C	1.0µm	N/A

The length and OD measurement results from the TM-006 sensor show that the sensor is capable of achieving the desired process repeatability requirement. Also, because the sensor does not depend on an external lighting source, one can expect the actual process measurement results to be similar to what was found on the testbed, assuming the sensor can be adequately protected from debris and contamination.

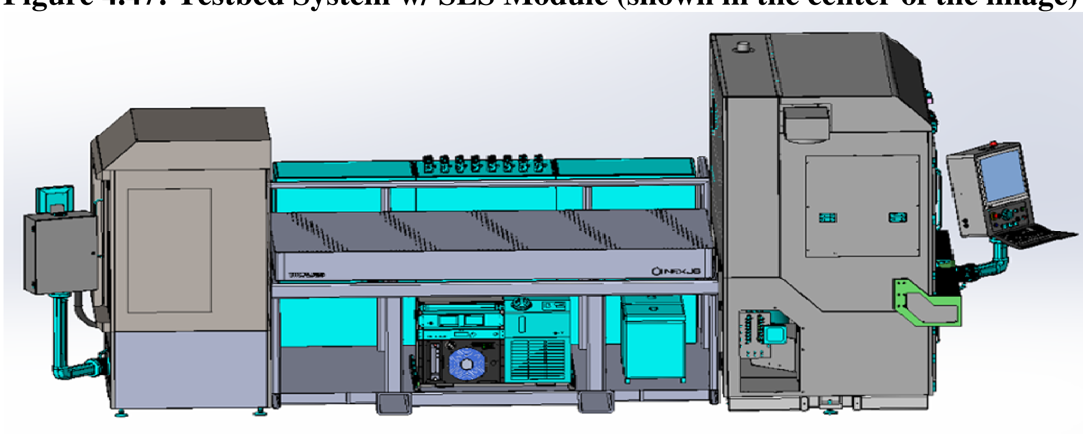
For the wall thickness measurements using the different imaging sensors, it was found that the results were largely dependent on lighting conditions and the ability of the sensor to detect contrast between the tube edge and the background of the image. The larger CMOS sensor in the CA-H2100M camera created the best image by far. The testing results from this sensor were well within the target process specifications. However, it was very difficult to achieve lighting conditions with the XG-500C sensor to capture an acceptable image.

Even with the best conditions, the sensor would occasionally detect a "false edge", which happened three times during the 30 samples that were taken. With the XG-200C sensor, lighting conditions could not be achieved to detect the edge of the tube; therefore no data could be captured. Based on this information, the clear sensor choice to use for wall thickness measurements is the CA-H2100M.

3) SLS Module

The third section of the testbed is the SLS module. The function of this module is to provide a flexible space where laser output modules can be installed and the laser light can be routed to either or both of the MAxHP and HLTP modules. Figure 4.47 depicts the SLS module in the center of the image, between the other two modules. The module consists of a large optical table that can support laser output modules and beam path components to feed the laser light to the back-side of each of the other two modules. The SLS module also contains the electrical cabinets for the entire system (back of the image) as well as the chillers and other controllers (front center of the image). As planned, the components and system design of the SLS module provides the capabilities as described in the SMART milestone for this subtask.

Figure 4.47: Testbed System w/ SLS Module (shown in the center of the image)



In parallel with the design effort, Microlution worked with potential customers to obtain additional information about the market requirements for these applications. Table 4.10 provides a summary of the additional market information compared with the DOE subtask evaluation criteria.

Table 4.10: Additional Market Requirements Compared w/ DOE Subtask Evaluation Criteria

Item	Goal Description	Concept to meet goal	Risks
1	Cylindrical parts 10mm dia, 20mm long	Centering chuck on multi-axis module, ability to chuck parts in tube laser module	
2	Tubes 1-10mm diameter, 1m long	Spindle on tube laser module	Customer sizes only go to 6mm. Desinging for 10mm may compromise performance.
3	Flat disc parts up to 300mm diameter, 10mm thick	Special rotary axis on multi-axis module	
4	5-axis motion, 25X/Y, 40Z, 45tilt, 360 rotary	Multi-axis module with improved C-axis design	
5	Tube laser motion, 300mm axial, 25mm radial, 360deg rotation	Tube laser module	Customer requirements only go to 200mm. Designing for 300mm may compromise packaging.
6	Femtosecond laser processing	Large optical table capable of multiple different laser sources	
7	Mechanical drilling using 0.1-6.0mm tools	Station on multi-axis module with HSK-E20 milling spindle	
8	Vision measurement for <0.5mm features, 0.01mm accuracy	Multi-sensor station on multi-axis module with Keyence measurement camera	
9	Depth measurement of features, 0.01mm accuracy	Multi-sensor station on multi-axis module with confocal sensor and touch probe	
10	Tube diameter measurement, 1-10mm diameter, 0.005mm accuracy	Multi-sensor station on tube laser module	Packaging challenges related to 10mm diameter capacity
11	Tube thickness measurement, 0.1-1mm thick, 0.01mm accuracy	Multi-sensor station on tube laser module	Packaging challenges related to 10mm diameter capacity

As described in Table 4.10, there are two DOE evaluation criteria that exceed the requirements of the market. First, the maximum tube diameter required for the market is 6mm, compared with 10mm proposed for the DOE criteria. Second, the market requires a maximum 200mm Z stage travel on the tube processing module, compared with 300mm proposed for the DOE criteria. After discussion, the team decided to design the testbed based on the commercial specifications rather than the original project specifications.

Subtask 5.2 Build and Test Multi-Application Testbed
Build and test a testbed system that provides an application platform to be used to develop and prove production processes for the identified applications.
Milestone 5.2.1 Demonstrate testbed system meets or exceeds performance criteria
The SMART milestone for this subtask is to demonstrate that the testbed meets or exceeds the criteria listed in Milestone 5.1.1.

The three main components of the multi-application testbed (MAxHP module, HLTP module, and SLS area) were built and then assembled as a complete testbed system. Images of different parts of the testbed are shown in Figure 4.48 thru Figure 4.56.

Figure 4.48: MAxHP Module

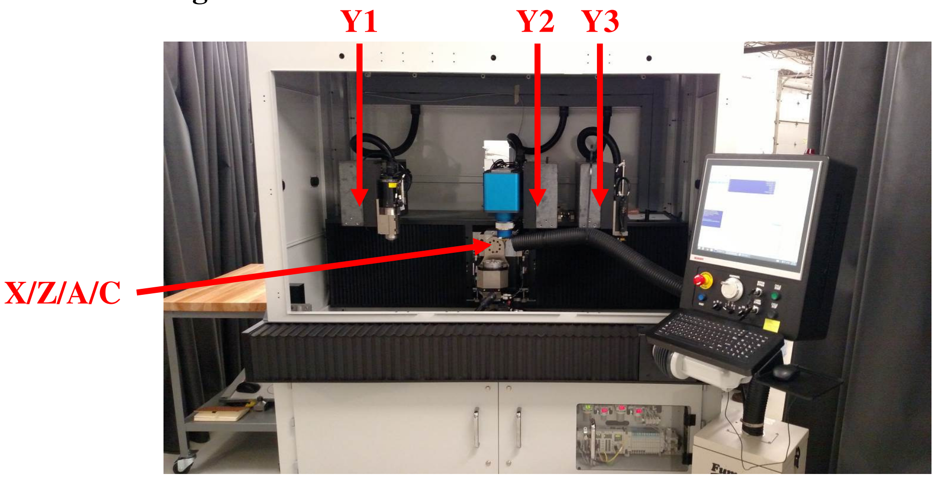


Figure 4.49: X/Y/A/C Stage

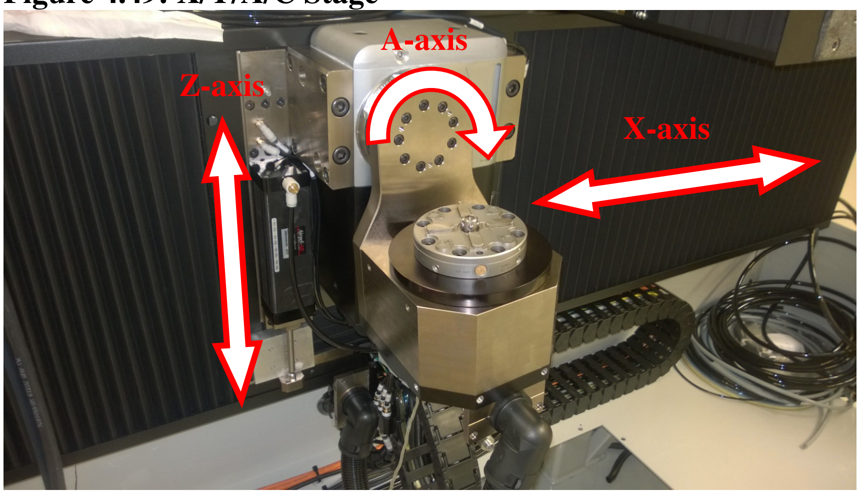


Figure 4.50: Y1 Stage w/ Spindle

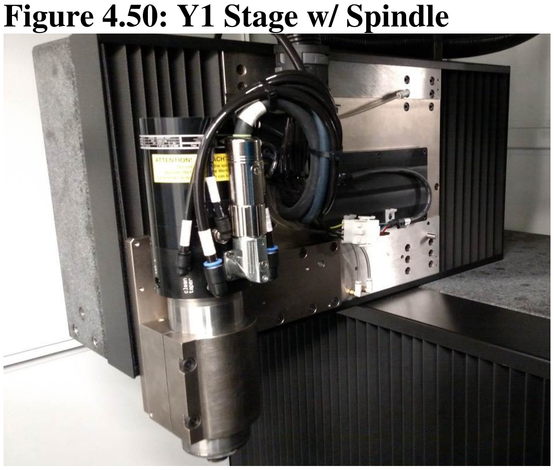


Figure 4.51: Y3 Stage w/ Camera & Touch Probe

Figure 4.52: HLTP Module (front)

Figure 4.53: HLTP Module Motion Platform

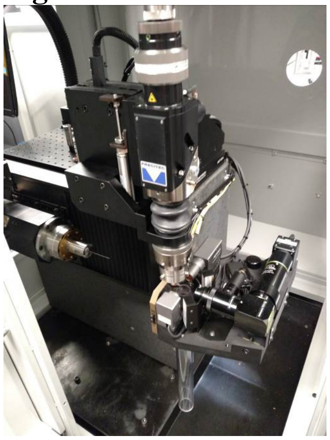


Figure 4.54: HLTP Module Cutting & Measurement Zone

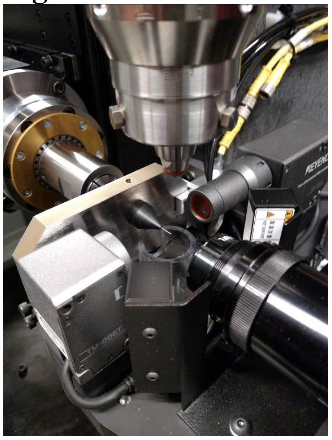


Figure 4.55: SLS Area

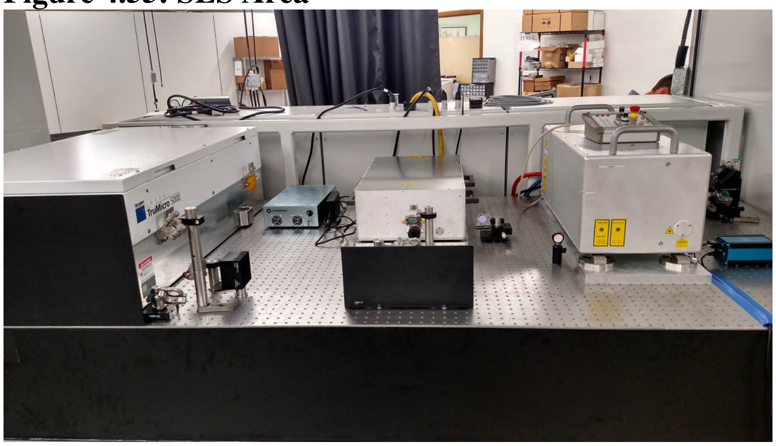


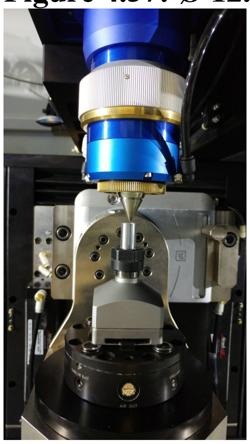
Figure 4.56: Electrical Cabinets & Pneumatics (side of testbed)

All testing to demonstrate that the testbed meets or exceeds the measurable criteria listed in Milestone 5.1.1 was completed and test data collected for each criteria.

Test Conditions and Method of Measurement & Test Results and Milestone Verification Data (Workholding Capability):

Cylindrical parts up to 10mm in diameter and 20mm long
Both the MAxHP module and HLTP module can hold cylindrical parts up to at least 10mm in diameter and 20mm long. Figure 4.57 shows a 12.7mm diameter cylindrical workpiece that is 45mm long, fixtured into the MAxHP module and ready for processing.

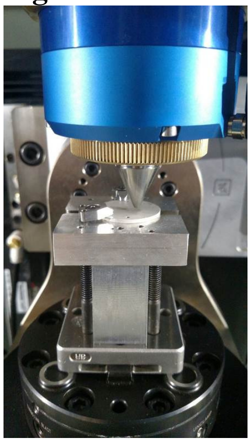
Figure 4.57: Ø 12.7mm, 45mm Long Cylindrical Piece Fixtured in MAxHP Module



Tubes with 1-6mm diameter, up to 1m long
The HLTP module has a rotary stage with workholding and the capability to clamp tubes that are within the range of 0.1mm to 12.7mm in diameter. The rotary stage was designed with an open center core so that the tubing can pass through the center of the stage and out the side of the machine. With proper support of the back end of the tube, lengths of tubing up to 1m can easily be processed by the HLTP module.

Flat disc parts up to 300mm diameter and 10mm thick
A custom flat stock fixture was designed to hold flat disc parts up to 10mm thick and any diameter or shape that fits into the working volume of the machine.
Figure 4.58 shows an image of the custom flat stock fixture. The clearance around the fixture inside of the machine allows for a part as large as 400mm in diameter without causing a collision.

Figure 4.58: Flat Stock Fixture in MAxHP Module (w/ sample secured)



Test Conditions and Method of Measurement & Test Results and Milestone Verification Data (Motion Capability):

5-axis motion: 25mm X/Y, 40mm Z, 45° tilt, 360° rotation

Table 4.11: Measured Travel Limits for MAxHP Module

Stage	Travel
X	1210mm
Y1, Y2, Y3	100mm
Z	45mm
A (tilt)	90°
C (rotation)	360°

Tube cutting motion: 200mm axial, 25mm focus, 360° rotation

Table 4.12: Measured Travel Limits for HLTP Module

Stage	Travel
X	200mm
Y	75mm
Z (focus)	72mm
C (rotation)	360°

Flat disc parts: ability to reach features on 300mm diameter disc

With 1210mm of X travel and 360° of C-axis rotation, the MAxHP module is capable of reaching features on a 300mm disc.

Test Conditions and Method of Measurement & Test Results and Milestone Verification Data (Accuracy):

Linear stage accuracy of +/- 1 micron

The linear stage accuracy of the testbed system is driven by several factors. The first is the accuracy of the component parts of the system, primarily the accuracy of the linear encoders. Below are error plots for the Heidenhain glass scale encoders used in the testbed system.

Figure 4.59: X Stage Encoder Position Error Plot

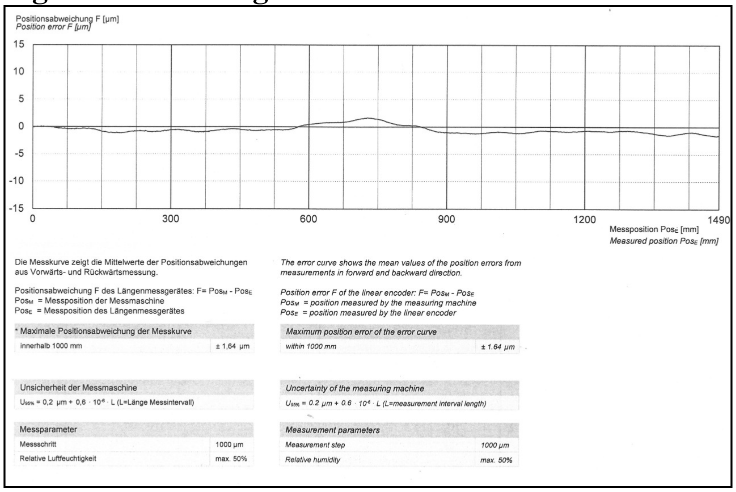


Figure 4.60: Y1 Stage Encoder Position Error Plot

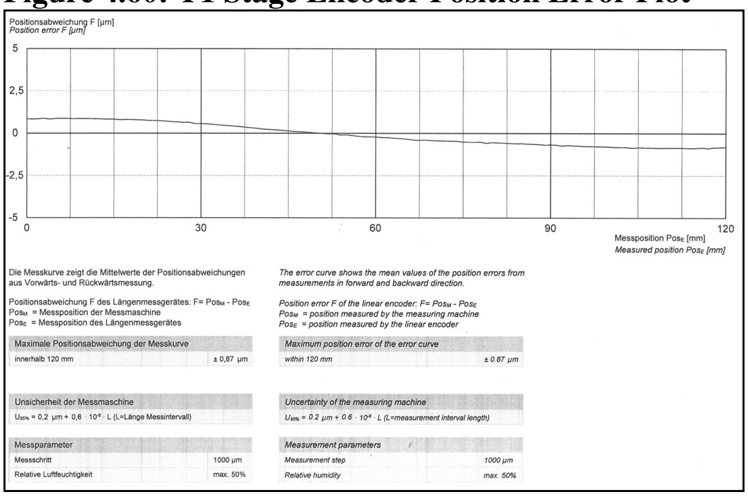


Figure 4.61: Y2 Stage Encoder Position Error Plot

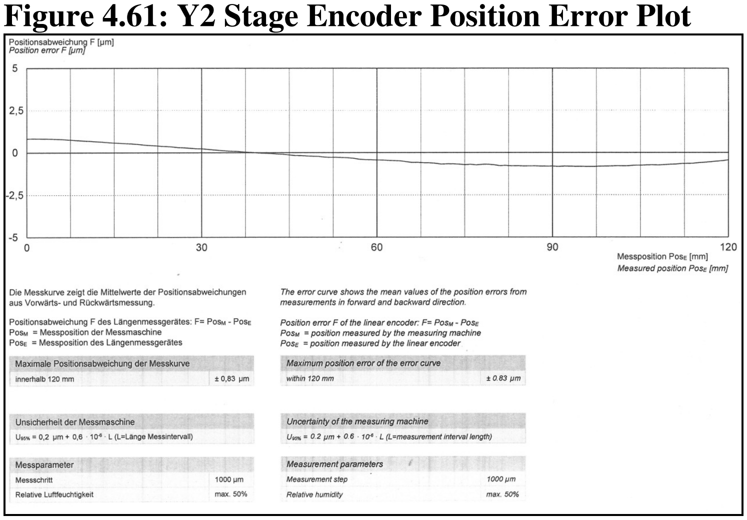


Figure 4.62: Y3 Stage Encoder Position Error Plot

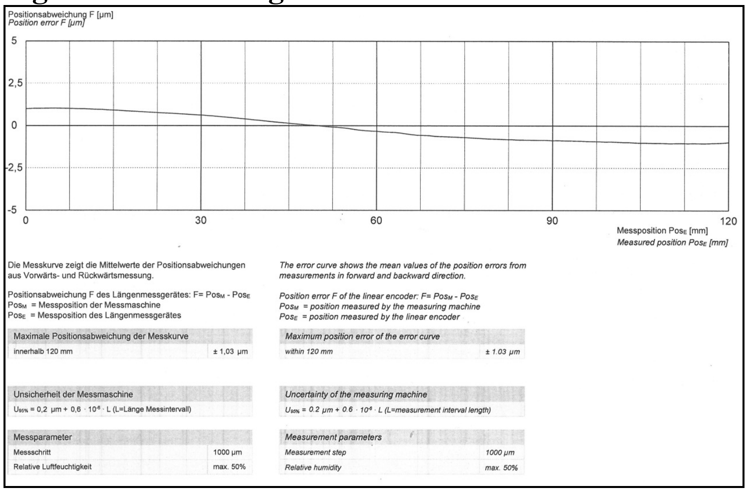
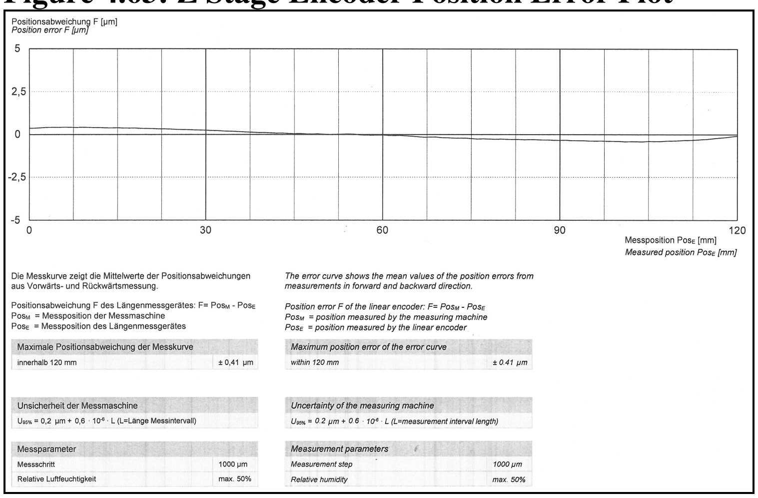


Figure 4.63: Z Stage Encoder Position Error Plot



The accuracy capability of a Microlution machining center is measured using a Renishaw XL-80 laser interferometer with a linear accuracy of 50 ppm. Measurements are taken by the laser at 10mm increments and then compared to the encoder reference values reported by the machine. Software compensations are made to adjust the stage positions to match the laser measurements. Figure 4.64 thru Figure 4.70 are plots of the measurement results of compensated stages for a Microlution laser processing center built after the testbed system.

Figure 4.64: Linear Calibration Results of X-Axis Under Y1 Station

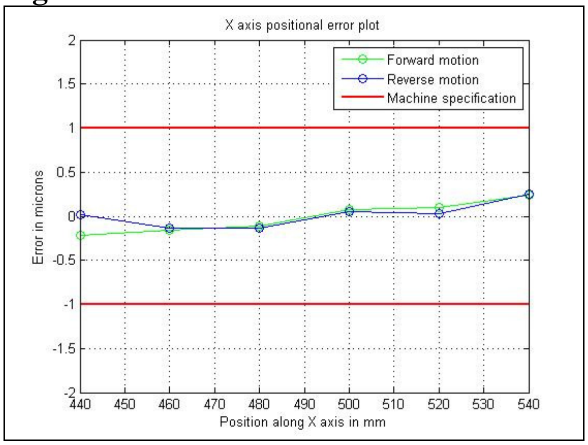


Figure 4.65: Linear Calibration Results of X-Axis Under Y2 Station

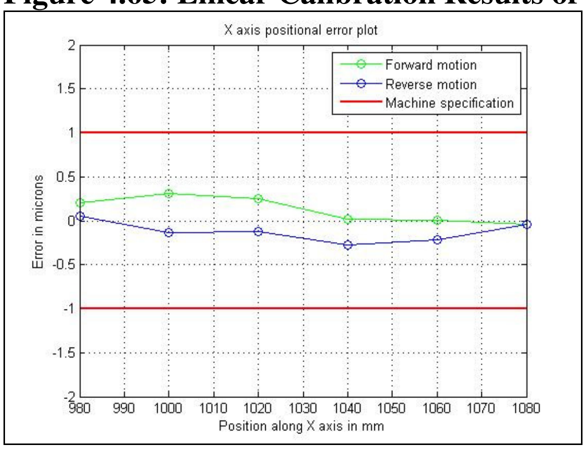


Figure 4.66: Linear Calibration Results of X-Axis Under Y3 Station

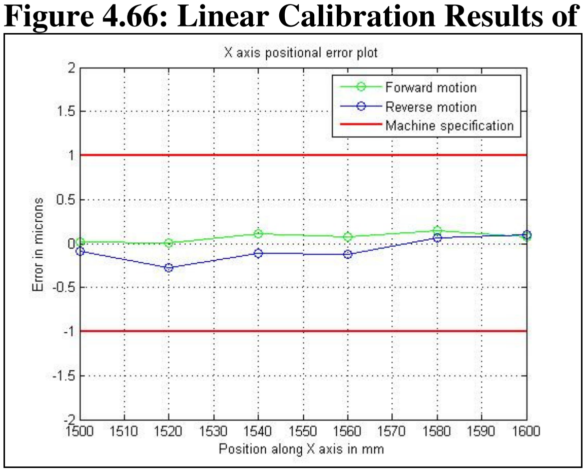


Figure 4.67: Linear Calibration Results of Y1-Axis

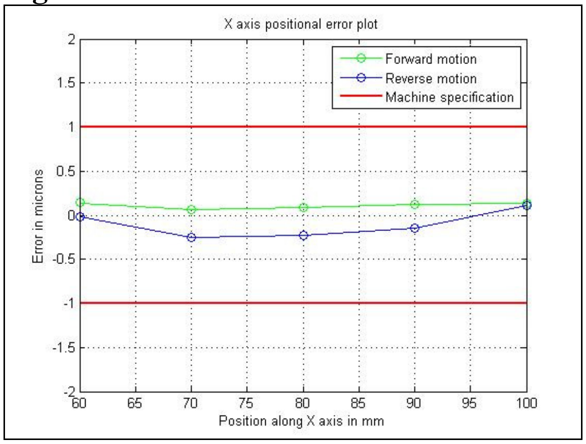


Figure 4.68: Linear Calibration Results of Y2-Axis

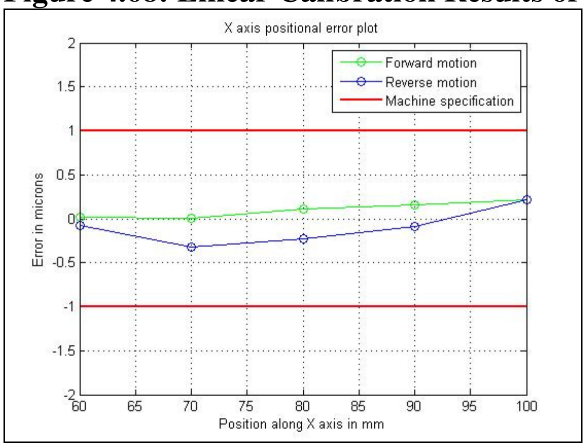


Figure 4.69: Linear Calibration Results of Y3-Axis

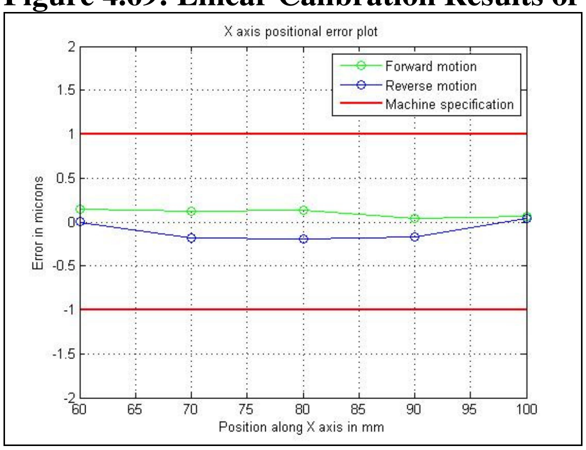
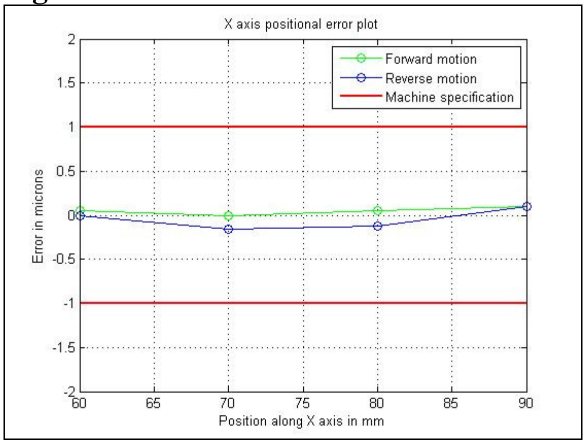


Figure 4.70: Linear Calibration Results of Z-Axis



The accuracy of the testbed system was also demonstrated in other Budget Period 2 subtasks. For example, in Subtask 8.1, a sample of 10 marker bands were cut using the HLTP module of the testbed. The target length for the part was 0.500mm and the system was able to cut the 10 parts to an average length of 0.5003mm. This demonstrates the accuracy capability of the linear stages of the system.

Test Conditions and Method of Measurement & Test Results and Milestone Verification Data (Processing/Measurement Capabilities):

Femtosecond laser processing

The capability to achieve femtosecond laser processing on the multi-application testbed was demonstrated in Subtasks 6.1, 7.1, 7.2, 8.1, and 8.2.

Mechanical milling/drilling using 0.1-6mm diameter tools

Mechanical milling/drilling was demonstrated in Subtask 8.2. The spindle installed on the testbed is an SC 3062 spindle from Fischer Precise with ISO #10 taper clamping system. This system is capable of supporting collets for any size tool shank up to 6mm. Collets are available for this at standard sizes down to 0.1mm.

Vision measurement of features < 0.5mm in size with measurement accuracy better than 10 microns

Vision measurement of marker band tubes was demonstrated in Subtask 8.1. The ID of the tube was measured using a Keyence 21MP, 4/3" CMOS camera with 8X lens. The nominal ID of the tube being measured was 0.406mm. Table 4.13 summarizes the uncalibrated measurement data for a sample of 10 parts that were measured. These results show that the average measurement value is within 10 microns of the nominal value and the measurement repeatability is sufficient enough that the machine could be calibrated such that all measurements are within this target level.

Table 4.13: Tube ID Measurement Results Using Keyence Vision System

Sample	ID (um)
1	396.6
2	398.6
3	395.6
4	399.2
5	398.8
6	399.0
7	398.9
8	397.5
9	398.7
10	398.6
Standard Deviation (2σ)	2.4
Average	398.1

Depth measurement of features with accuracy better than 10 microns

The depth measurement capability of the system was demonstrated by performing a test of the touch probe system on the MAxHP module of the testbed. For this test, a sample of 25 measurements were taken on a workpiece surface at two different feed rates. Table 4.14 shows the results of the tests. These results show that the system is capable of depth measurement to a very repeatable level and that it can be calibrated to measure any feature to an accuracy of better than 10 microns.

Table 4.14: Depth Measurement Results Using Touch Probe

Trial	Z Location (mm)	
	10 mm/min	100 mm/min
1	0.00022	0.00538
2	0.00056	0.00538
3	0.00014	0.00538
4	0.00056	0.00455
5	0.00039	0.00705
6	0.00031	0.00455
7	0.00014	0.00455
8	0.00014	0.00621
9	0.00014	0.00455
10	-0.00003	0.00371
11	0.00014	0.00538
12	0.00006	0.00538
13	-0.00003	0.00621
14	0.00031	0.00371
15	0.00006	0.00455
16	0.00039	0.00455
17	-0.00003	0.00538
18	0.00031	0.00538
19	-0.00011	0.00538
20	0.00022	0.00455
21	0.00022	0.00371
22	0.00031	0.00621
23	-0.00003	0.00538
24	-0.00003	0.00455
25	0.00006	0.00371
Standard Deviation (2σ)	0.00036	0.00174

Tube diameter measurement of tubes 1-6mm diameter with measurement accuracy better than 5 microns

Tube diameter measurement capability was demonstrated in Subtask 8.1. As part of the criteria for this subtask, the tube OD of 10 sample parts was measured using a 2D Keyence laser micrometer. The nominal OD of the measured tube was 0.513mm, which was measured using a calibrated vision system. Table 4.15 summarizes the uncalibrated measurement data for a sample of 10 parts that were measured on the HLTP module. These results show that the average measurement value is within 5 microns of the nominal value and the measurement repeatability is sufficient enough that the machine could be calibrated such that all measurements are within this target level.

Table 4.15: Diameter Measurement Results Using Keyence 2D Laser Micrometers

Sample	OD (um)
1	516.6
2	516.8
3	516.8
4	516.4
5	516.3
6	516.6
7	516.4
8	516.2
9	516.5
10	516.8
Standard Deviation (2σ)	0.4
Average	516.5

Tube thickness measurement of tubes 0.1-1mm thick with measurement accuracy better than 10 microns

Tube thickness measurement capability was demonstrated in Subtask 8.1. As part of the criteria for this subtask, the wall thickness of 10 sample parts was measured using a combination of a Keyence 21MP, 4/3" CMOS camera with 8X lens to measure ID and a 2D Keyence laser micrometer to measure the OD of the part. The nominal wall thickness of the measured tube was 50.8µm. Table 4.16 shows the resultant measurements of the wall thickness derived from the direct measurements of the OD and ID from the two sensors. These results show that the average measurement value is within 10 microns of the nominal value and the measurement repeatability is sufficient enough that the machine could be calibrated such that all measurements are within this target level.

Table 4.16: Wall Thickness Measurement Results

Sample	Wall Thickness (um)
1	60.0
2	59.1
3	60.6
4	58.6
5	58.7
6	58.8
7	58.7
8	59.4
9	58.9
10	59.1
Standard Deviation (2σ)	1.3
Average	59.2

Using the two sensor method to derive the wall thickness of the tubing, it is possible to measure any wall thickness, as long as the feature being measured is within the field of view of both sensors. Therefore, the requirement for the ID is < 1.8mm (which is the vertical size of the field of view of the camera) and the requirement of the OD is < 6mm (which is the field of view of the laser micrometers). An alternative method is to use the camera to directly measure the wall thickness of the tube. In this case, it is possible to measure the wall thickness for any tube OD size, as long as the wall thickness is less than the horizontal field of the camera, which is 2.2mm. Therefore, the criteria for the tube thickness measurement have been met.

Task 6.0 Advanced Control Development for Coordinated Motion and Laser Firing

Subtask 6.1 Multi-Axis High/Low Frequency Coordination

Demonstrate the ability to separate 5-axis trajectory into high frequency/low frequency components, execute motion on testbed, and achieve desired machining result.

Milestone 6.1.1 Demonstrate advanced control with multi-axis high/low frequency coordination

The SMART milestone for this subtask is a demonstration of the control system's capability to separate a 5-axis trajectory into high and low frequency components and execute a cutting process accordingly. The specifications of the 5-axis trajectory will be that it includes simultaneous 5-axis motion with frequency components less than 20Hz and frequency components above 100Hz. The demonstration should show executed trajectory accuracy better than 10 microns and an execution time of no more than 10% longer than the nominal trajectory time.

The control architecture must accommodate the:

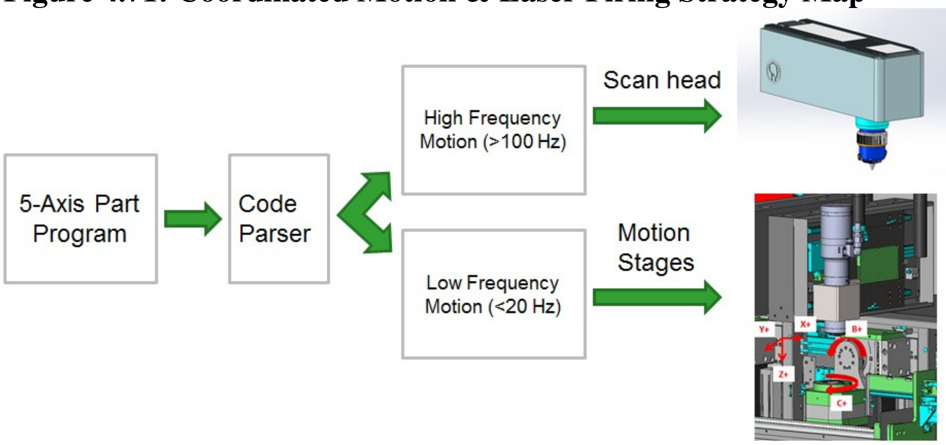
- High-level 5-axis trajectory evaluation and separation into its different frequency components;
- Real-time control of the 5-axis machine and the optical scanner;
- Coordination of the 5-axis machine and the optical scanner and;
- Other system requirements such as a user interface, system safety functionality, general I/O, and other components.

The control system may include multiple components such as:

- A windows-based PC for the user interface and other possible functions;
- A real-time machine controller for the operation of the servo stages, high-speed I/O, some safety functionality, and other possible functions;
- Individual servo drives for the operation of the servo loop and some safety functionality;
- Stand-alone controllers for the laser output system, laser scanner system, some sensors, and other possible items and;
- Stand-alone PLC controllers for simple sub-system control and (possibly) master coordination of the entire system.

As shown in Figure 4.71, the process starts with a 5-axis part program. The program is then sent through a code parsing program. The code parser separates the program into two programs, one with the higher frequency motion and one with the lower frequency motion. The program with the higher frequency motion is used by the HP scan head, which uses high frequency galvos to manipulate the laser beam. The low frequency motion is handled by the motion stages. A clock signal, generated by an encoder from the motion stages, is sent to the HP scan head to synchronize the two systems.

Figure 4.71: Coordinated Motion & Laser Firing Strategy Map



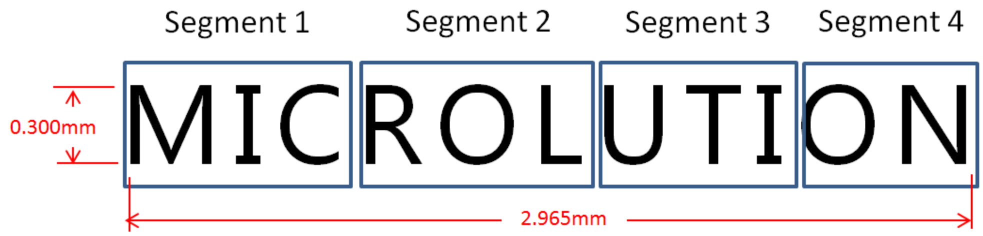
Test Conditions and Method of Measurement:

The sample to be machined was designed and the code for the 5-axis motion program was generated. A feature was successfully machined using a hybrid strategy as described in the criteria for Milestone 6.1.1. The feature was an etching of the word "MICROLUTION" into a flat, stainless steel coupon. The hybrid strategy was achieved by separating the required motion into two separate components of the MAxHP module. The high frequency motion was performed by the HP scan head and the low frequency motion was performed by the motion stages of the MAxHP. The overall target size of the feature is 0.3mm tall by 2.965mm wide. However, the working field of the HP scan head is only 1mm. Therefore, the HP scan head traced the individual shapes of the letters while the motion stages performed the rough linear positioning required for the HP scan head to reach the entire feature.

In order to synchronize the motion between the HP scan head and the motion stages, the encoder signal from the X-axis of the motion stages was connected to the HP scan head. The X-axis encoder was a Heidenhain linear glass scale with EnDat 2.0 interface. This was connected to a Yaskawa servo drive, which then interpreted the signal and output a 5Vpp TTL signal to match the pulse train of the encoder signal. This TTL signal was then connected to an input on the scan head controller.

Four separate scan head recipes were written to divide the feature into segments small enough to fit into the HP scan head's working field. Figure 4.72 shows how the feature was divided into the separate sections. Once the recipe was started, the HP scan head executed the individual segments as the encoder signal read from the X-axis reached specific positions. For example, the HP scan head ran the first segment after 80 counts, ran the second segment after 1200 more counts, and so on until all four segments were completed. Three axes of motion were performed by the HP scan head (X, Y, and Z), and the HP scan head was moved in two axes by the motion stages (X and Y) for a total of 5-axis motion.

Figure 4.72: Feature Etched & Individual Segments Processed by HP Scan Head

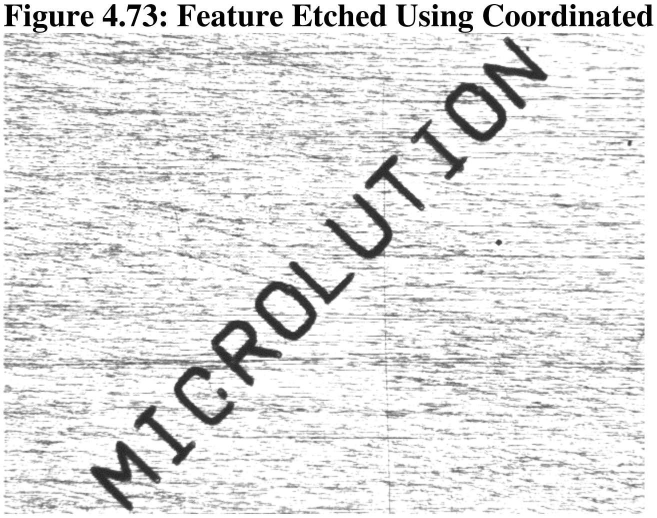


The laser used for this application was a Coherent Monaco with capability of <400fs pulse width, 1035nm wavelength, repetition rate up to 1MHz, and 40μJ pulse energy (max 40W average power). The laser was fixed to the optical table of the SLS area and the beam was directed through several fold mirrors before entering the HP scan head. The pulse energy used to make the feature was the full 40μJ, but the repetition rate was only set to 20kHz (0.8W average power) because it was not intended to cut through the material.

Test Results and Milestone Verification Data:

Figure 4.73 shows the resulting feature that was machined using the coordinated motion strategy described above. The overall size of the feature was measured at 0.299mm tall by 2.970mm wide, which is within 10 microns of the target size. The scan speed used to process the feature by the HP scan head was 4500mm/min. Although not tested, it is estimated that the system would not be able to create this feature without the HP scan head to the accuracy specification at a speed above 2000mm/min. Therefore, the coordinated motion strategy is able to achieve a much more efficient trajectory than the traditional method.

Figure 4.73: Feature Etched Using Coordinated Motion Control



Task 7.0 Laser Processing Strategy Development

Subtask 7.1 Precious Metal Drilling for Cardiac Catheter Devices

Using the testbed, demonstrate the ability to produce typical precious-metal holes for cardiac catheter devices with dimensions of 0.075mm diameter, 0.450mm depth and less than 2 degree taper.

Milestone 7.1.1 Demonstrate precious metal drilling performance
The SMART milestone for this subtask is to demonstrate a process cycle time of 3 seconds or less for typical precious-metal holes for cardiac catheter devices with dimensions of 0.075mm diameter, 0.450mm depth, and less than 2 degree taper.

Test Conditions and Method of Measurement:

Holes were successfully drilled through a precious metal material that met the criteria outlined in Milestone 7.1.1. The subtask was completed using the MAxHP module of the multi-application testbed along with an ultrashort pulsed laser and 5-axis HP scan head.

The laser used to drill the holes was a TruMicro 5050 Femtosecond Edition, with pulse duration of 900fs, 1030nm wavelength, repetition rate of 200kHz, and 50μJ pulses (10W average power). The laser was fixed to the optical table of the SLS area of the testbed and the beam was directed to the 5-axis HP scan head through several fold mirrors. The HP scan head used was an Arges Precession Elephant scan head which can manipulate the beam in three axes of translation and two axes of tilt. All five axes of motion that are available in the HP scan head were utilized to drill the precious-metal holes.

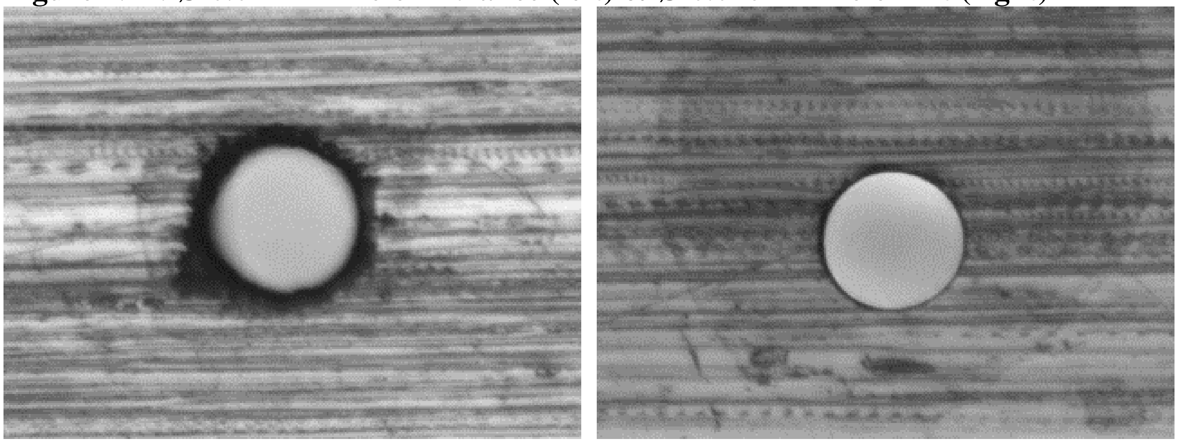
The material used was 99.9% pure silver and 0.511mm thick. The material was cut into 1" square coupons so that it could be easily fixtured into the MAxHP module. The coupon was secured to the custom flat stock fixture attached to a System 3R pallet as shown in Figure 4.58. The MAxHP module has a corresponding System ER chuck which allows the pallet to be easily removed and repeatedly re-installed into the machine.

Test Results and Milestone Verification Data:

The motion stages of the MAxHP module positioned the nozzle of the HP scan head at a fixed distance above the silver coupon. A custom laser drilling recipe was then run on the HP scan head that was developed specifically for this application and to achieve the cycle time, hole diameter, and taper criteria outlined in Milestone 7.1.1. The dimensions of the resulting holes were 0.072mm at the entrance and 0.076mm at the exit with a taper angle of 0.45 degrees (

Figure 4.74). The total cycle time to run the drilling recipe was 1.7 seconds. Overall, the quality of the hole that was produced met or exceeded the requirements of the application.

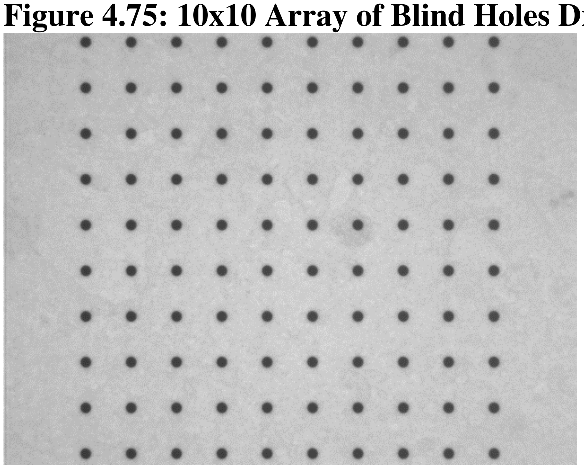
Figure 4.74: Ø 0.072mm Hole Entrance (left) & Ø 0.076mm Hole Exit (right)



Subtask 7.2 Ceramic Hole Drilling for Probe Cards
Using the testbed, demonstrate the ability to produce standard probe-card holes with dimensions of 0.075mm diameter, 0.650mm depth and less than 2 degree taper.
Milestone 7.2.1 Demonstrate ceramic hole drilling performance
The SMART milestone for this subtask is to demonstrate a process cycle time of 10 seconds or less for standard probe-card holes with dimensions of 0.075mm diameter, 0.650mm depth, and less than 2 degree taper.

A 10x10 array of blind holes was drilled into a ceramic sample to measure hole diameter, depth, shape, cycle time, and material removal rate (Figure 4.75).

Figure 4.75: 10x10 Array of Blind Holes Drilled Into A Ceramic Sample



Measurements of these holes showed very good diameter circularity, which was consistent from hole to hole (Table 4.17).

Table 4.17: Measureable Hole Attributes

Measurement	Result
Average Diameter	0.110mm
Average Depth	0.400mm
Cycle Time	6 seconds
Material Removal	0.0006mm^3/s

In order to achieve the desired 10 second cycle time for the specified hole, a material removal rate of at least 0.0003mm^3/s was required. A rate of twice that amount was achieved with this test pattern, while still maintaining excellent quality on both diameter circularity and entrance shape.

Test Conditions and Method of Measurement:

After further optimization to the drilling recipe, probe-card holes were drilled thru ceramic material that met the measurable criteria outlined in Milestone 7.2.1. The three large components used were an ultrashort pulse laser, a 5-axis HP scan head, and a high precision motion system.

The laser that was used to drill the probe-card holes was a Light Conversion Pharos laser with a pulse duration less than 300 femtoseconds, 1030nm wavelength, and 200kHz repetition rate with 50µJ pulses (10W average power). The beam was put through a beam expander to reduce the beam to a 1.4mm beam diameter, the diameter that the HP scan head required. No other beam shaping occurred before the HP scan head.

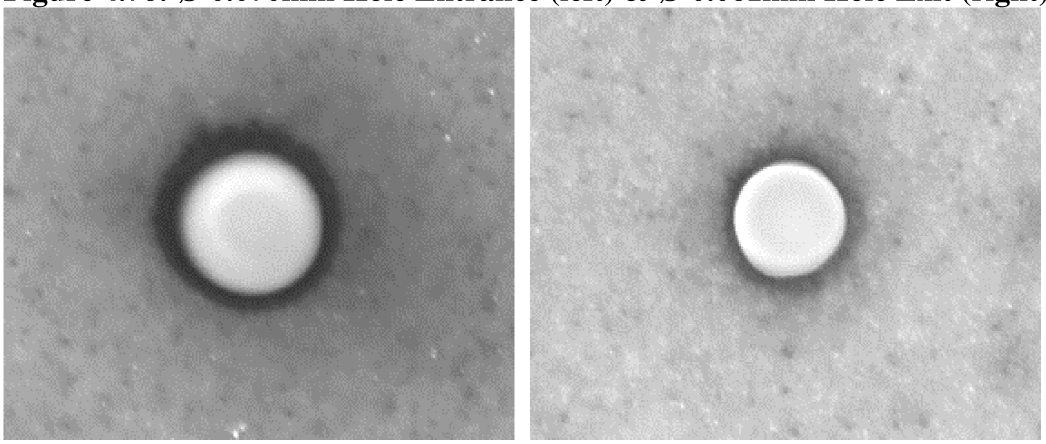
The HP scan head that was used was an Arges Precession Elephant scan head with 5-axis capabilities (three translation axes and two tilt axes). The 5-axis HP scan head was advantageous for this subtask as it allowed for taper control by tilting the beam around the X and Y axes.

The motion platform, built and designed by Microlution, was used to accurately and precisely move the part and was the central control for all the other systems (i.e. laser, scan head, cover gas). The custom flat stock fixture held the ceramic sample in such a way that the surface height of the workpiece was known, otherwise the laser focus position would change relative to the material. Figure 4.58 shows how the sample was fixtured for machining.

Test Results and Milestone Verification Data:

The holes drilled had a laser-entrance diameter of 0.070mm and laser-exit diameter of 0.061mm (Figure 4.76), or a full-angle taper of 0.79 degrees with a cycle time of 3.1 seconds. Although good results were achieved that satisfied Milestone 7.2.1, the high aspect ratio of the hole, combined with the relative size of the hole diameter to the beam diameter limits the amount of control over the taper. Further improvements of the taper angle may be possible by increasing the beam focus spot size, therefore reducing the beam divergence.

Figure 4.76: Ø 0.070mm Hole Entrance (left) & Ø 0.061mm Hole Exit (right)



Task 8.0 Hybrid Machining Strategy Development

Subtask 8.1 In-Situ Measurement for Laser Tube Processing for Marker Bands
Using the multi-process testbed, simultaneously cut and measure tube diameter, wall thickness, and part length to 0.01mm accuracy.
Milestone 8.1.1 Demonstrate tube cutting process
The SMART milestone for this subtask is to demonstrate a process cycle time of 2 seconds or less to cut and measure a 0.500mm diameter, 0.500mm long, 0.050mm wall thickness tube.

Test Conditions and Method of Measurement:

Tubes were successfully cut that met the criteria outlined in Milestone 8.1.1. The task was completed using the HLTP module of the multi-application testbed along with an ultrashort pulsed laser from the SLS area. The material used was 304 stainless steel with a nominal OD of 0.02" (0.508mm) and nominal ID of 0.016" (0.406mm), for a nominal wall thickness of 0.002" (0.051mm).

The laser used for this application was a Coherent Monaco with capability of <400fs pulse width, 1035nm wavelength, repetition rate up to 1MHz, and 40μJ pulse energy (max 40W average power). The laser was fixed to the optical table of the SLS area and the beam was directed through several fold mirrors into a Precitec fixed optic cutting head mounted inside the HLTP module. The cutting head was positioned at a fixed distance above the top of the tube using the Y and Z axes of the HLTP module. The tube was fed underneath the head using the X-axis of the HLTP module, which was used to control the length of the part being cut. Once the tube was in position to be cut, it was rotated using the high speed spindle for one full revolution with the beam focused on the top of the tube. A delrin guide bushing was used to support the end of the tube close to the cutting zone to minimize the deflection of the tube.

Two sensors were used to measure the tube before and after it was processed. To measure the length and OD of the part, a 2D Keyence laser micrometer (model TM-006) was used with specified measurement accuracy of ±0.5µm, repeatability of ±0.06µm, and a measurement field of 6mm. The OD of the tube can be taken directly from the measurement prior to cutting off the part and the length of the part can be derived by the measurement of the end of the tube before and after processing.

Figure 4.77 shows an image taken from the 2D laser micrometers. To measure the wall thickness of the tube, a high resolution, 21MP Keyence camera was positioned to capture an image of the end of the tube.

Figure 4.77: 2D Keyence Laser Micrometer Image

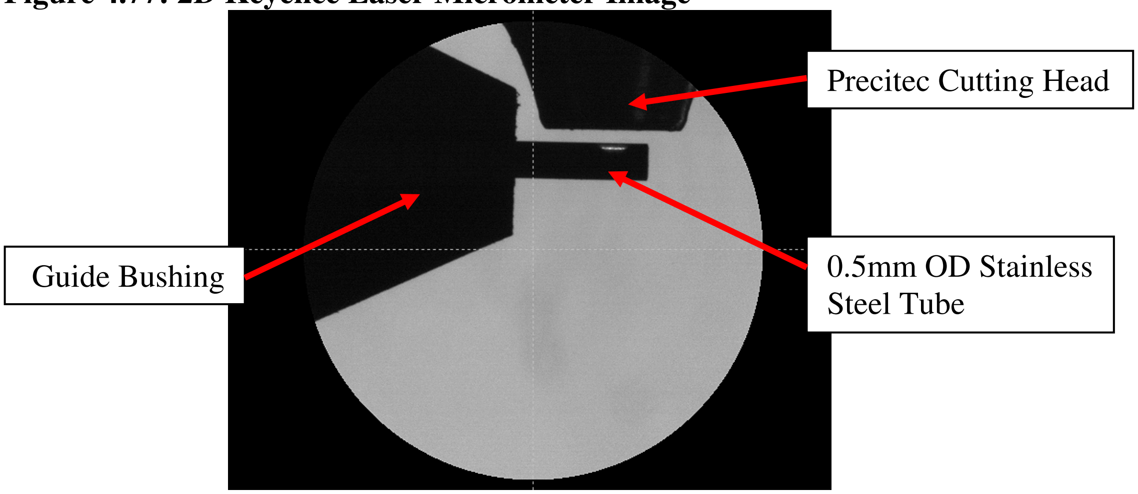


Figure 4.78 shows an image taken from the high resolution camera, with the green circle highlighting the measured ID of the tube.

Figure 4.78: High Resolution Camera Image Measuring Tube ID

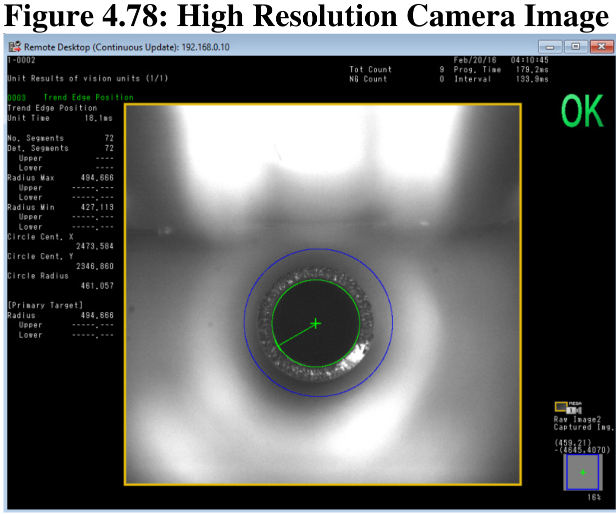
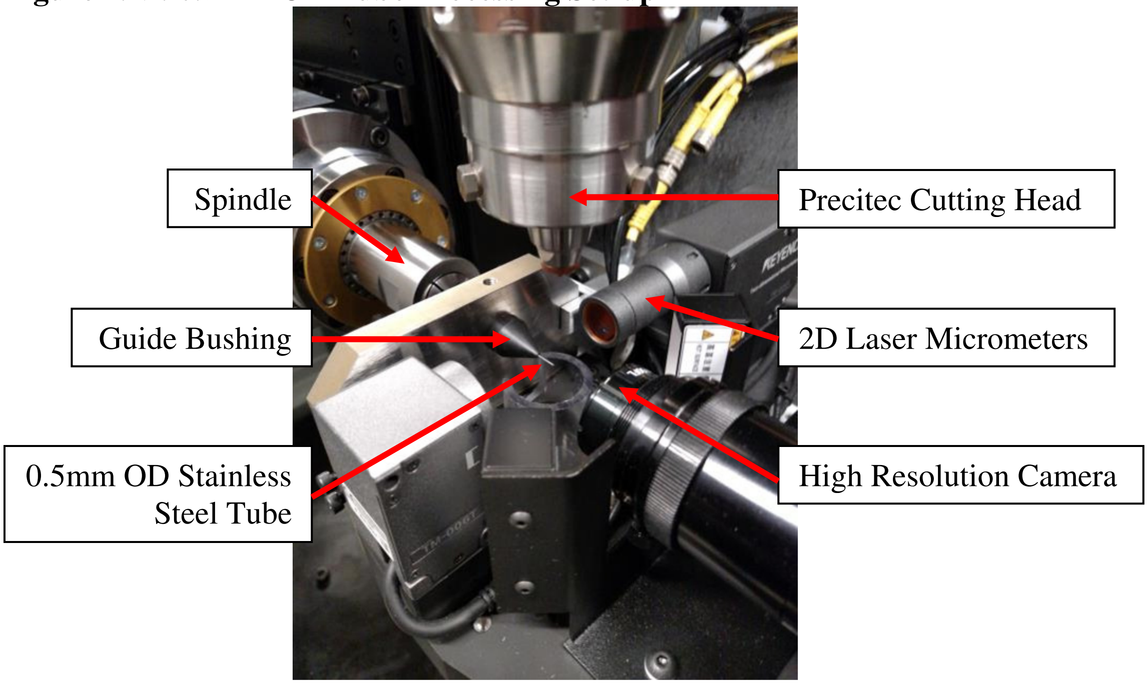


Figure 4.79 shows an overview of the entire set-up that was used to process the tube.

Figure 4.79: 0.5mm OD Tube Processing Set-up



Test Results and Milestone Verification Data:

One full rotation at a speed of 300 rpm was capable of cutting the part free from the tube with a cutting time of 0.2 seconds. Also, the time to make the required measurements with both sensors was approximately 1 second, for a total cycle time of 1.2 seconds which exceeds the 2 second criteria outlined in Milestone 8.1.1. Measurement results from a sample of 10 parts are shown in Table 4.18. Although no accuracy or repeatability specifications are outlined for Milestone 8.1.1, these results show excellent repeatability and accuracy close to the nominal values, especially for the length of the part (the dimension that is controlled by the system).

Table 4.18: Measurement Results from 10 Parts

Measurement	Nominal (µm)	Measured (µm)	2σ Repeatability (µm)
OD	508	516.5	0.43
Wall Thickness	51	51.1	2.41
Length	500	500.3	2.51

Subtask 8.2 Hybrid Machining for Test Sockets
Using the testbed, demonstrate the ability to produce milled and laser machined features within the tolerances described on a representative test-socket part.
Milestone 8.2.1 Demonstrate hybrid machining of test sockets
The SMART milestone for this subtask is to demonstrate a process that utilizes both milling and ultrafast laser cutting to produce features with a positional tolerance of ±0.012mm relative to each other. The milled feature will be a 1.100mm deep by 0.241mm diameter hole

and the laser cut feature will be a slot that meets the dimensional requirements of 0.051±0.009mm wide by 0.129±0.006mm long by 0.100mm thru.

Test Conditions and Method of Measurement & Test Results and Milestone Verification Data:

Hybrid machined slots were successfully cut that met the criteria outlined in Milestone 8.2.1. The MAxHP module of the multi-application testbed was used to mill out and ream the slots using an ultrashort pulsed laser from the SLS area and a mechanical spindle mounted on one of the stages. The material used was 0.015" (0.381mm) thick, hardened 420 stainless steel.

Slots were first milled out with a mechanical spindle. The workpiece was then positioned under the 5-axis HP scan head beam delivery system (Arges Precession Elephant v1.3). The 5-axis HP scan heads have the special capability to tilt the beam and therefore control the taper of the sidewall. The laser used was a Trumpf TruMicro 5050 Femstosecond Edition with 900fs pulse duration, 1030nm wavelength, 50µJ pulse energy, and 400kHz (20W average power). The HP scan head was set to keep a constant trace diameter of 0.010mm at a scan frequency of 350Hz and with the beam focus at the surface of the material. The workpiece was moved at a feed rate of 50mm/min during the reaming process.

A Mitutoyo vision system was used to measure and observe the reamed slots. 0.026mm of material was removed at the laser entrance and a 2.7 degree negative taper was measured along the cut face (see Figure 4.80 and Figure 4.81). The laser did a good job of removing the entrance burr caused by the mechanical cutting tool and created a smooth, consistent cut face (see Figure 4.82). The reaming feed rate of 50mm/min is typical for mechanical milling of a similar feature and should therefore allow for adding a process similar to this without adding to the overall cycle time of the parts.

Figure 4.80: Laser Entrance of Reamed Slot 10x Image

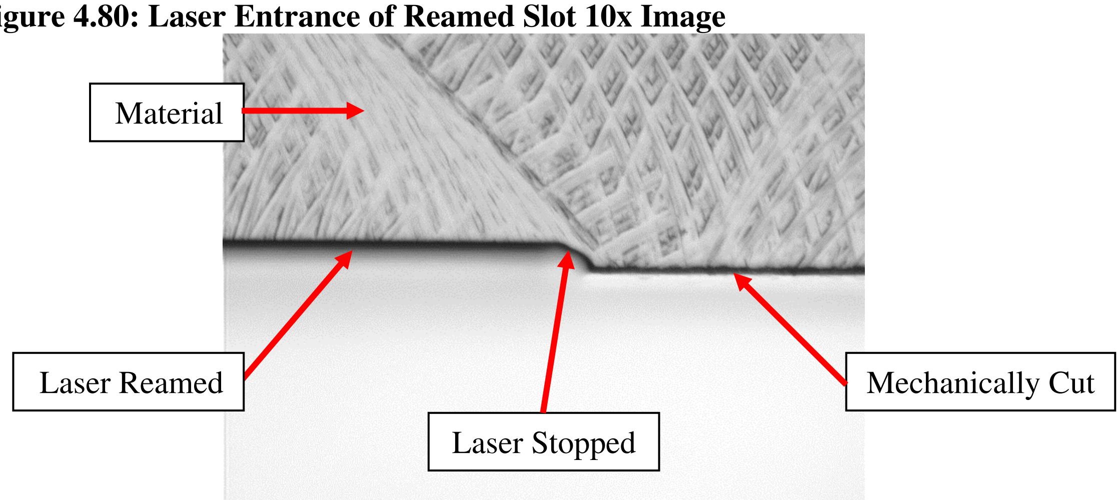


Figure 4.81: Laser Exit of Reamed Slot 10x Image

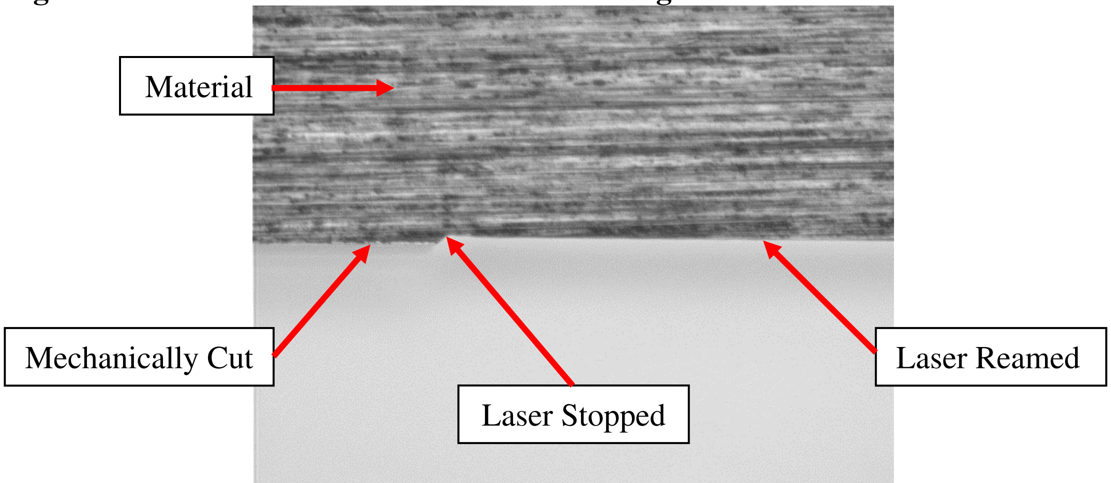
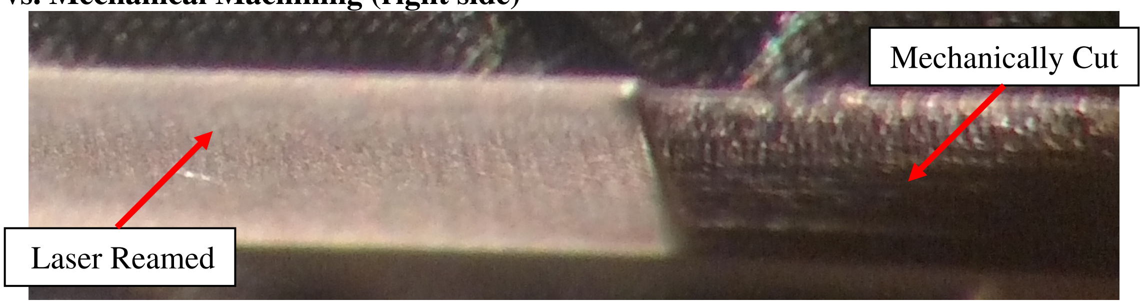


Figure 4.82: Low Magnification Image Showing the Cut Face Using a Laser (left side) vs. Mechanical Machining (right side)



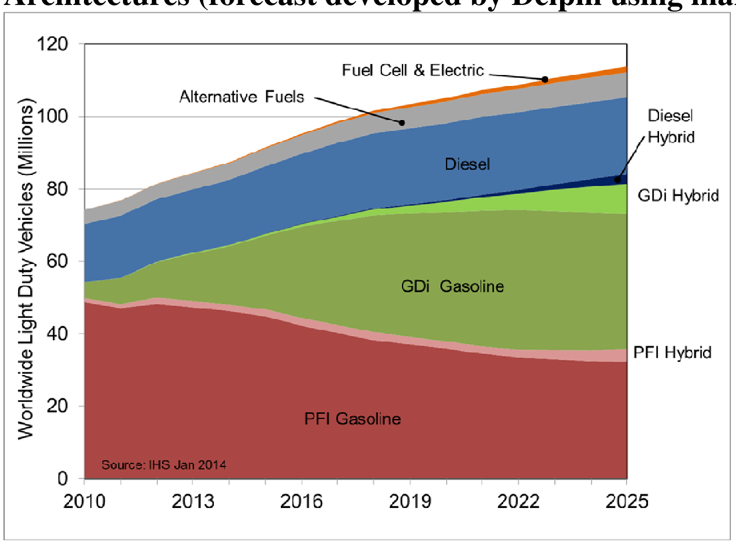
5. **Benefits Assessment**

The potential market, environmental, and energy benefits, as well as any cycle time improvements were calculated and the final benefits assessments for both Delphi and Microlution are documented below.

MARKET BENEFITS (Delphi): The technology is expected to have a substantial benefit to the overall US manufacturing capabilities. Ultrafast laser manufacturing is an emerging field with aggressive investment by competitor nations including South Korea, France, and Germany. Recent advances in the technology have been expanding the capabilities and application of the tool. This project provided an important understanding of how to best apply an ultrafast laser in concert with an integrated part / motion control system. This knowledge will enable far more industries to develop previously unproducible designs, increase their part quality, and maximize their factory throughput.

The number of GDi vehicles continues to rapidly increase in response to global requirements for fuel economy improvement and CO_2 reduction. Figure 5.1 depicts the growth of the GDi vehicle market worldwide as estimated by the marketing firm IHS. The number of GDi vehicles worldwide is expected to grow to 38.5M vehicles in 2020 (an increase of roughly a factor of 3 compared to 2013) and to 45.6M by 2025. It is not possible to attribute added jobs to any single GDi fuel injector innovation being developed. However, as the GDi market grows, an estimated additional 30 manufacturing related jobs will be created in the United States by 2020 to manufacture fuel injector nozzle seats for Delphi GDi fuel injectors.

Figure 5.1: Projected Global Market Penetration for Major Light Duty Powertrain Architectures (forecast developed by Delphi using market share data from IHS)



MARKET BENEFITS (Microlution): Microlution has a broad customer base within the target markets for this technology including medical, consumer electronics, aerospace, and other industries. Within those markets, ultrafast laser technology was previously not a viable option and therefore its use was limited to within the automotive industry. The results of this project have shown the commercial viability of these additional applications using laser technology. Microlution expects to deliver machines utilizing laser technology into these markets as a result of this project.

It is difficult to determine the exact number of US jobs that may be added due to this work. However, Microlution estimates that the technology developed as a result of this project will result in 10 additional US jobs at their plant in Chicago, IL. Microlution also expects that additional jobs will be created or retained at their customer sites as they purchase and operate machines using the developed technology.

ENVIRONMENTAL AND ENERGY BENEFITS (Delphi): The DOE provided Delphi a spreadsheet tool developed at Oak Ridge National Laboratory (ORNL) called “LIGHTenUP” (Lifecycle Industry GHgas, Technology and Energy through the Use Phase) for estimating environmental and energy benefits from manufacturing processes. Delphi met with Dr. Nimbalkar and Dr. Alkadi of ORNL to discuss this tool during the summer of 2013 and Delphi used LIGHTenUP to calculate energy and CO_2 reduction benefits for this project.

The baseline manufacturing method for fuel injector nozzle seat spray hole manufacturing established for this project is EDM. Dr. Nimbalkar and Dr. Alkadi provided baseline values for EDM power consumption and cycle time in LIGHTenUP. For a fuel injector nozzle seat with six spray holes (typical), these values are 4.1kW and 105 seconds, respectively. Delphi does not have independent experience in using EDM for mass production of fuel injector nozzle seat spray holes so Delphi has retained these baseline values for analysis.

Table 5.1 compiles pertinent information for GDi fuel injector nozzle seat manufacturing using EDM and laser-based techniques. The first three columns are relevant for discussion based on Delphi’s current project status. The fourth column (shaded gray) represents further improvements Delphi expects to make when developing the next generation machine. It is important to note that the columns labeled “Start of Project” and “End of Project” for Delphi’s laser processing method represents Delphi’s production status so that the improvements reflected under the “End of Project” column compared to “Start of Project” represent learnings from the project whose benefits have already been transferred from the prototype development platform to a production environment (i.e. 10W laser, 1 piece collet – 3 jaw chuck work holding tooling).

Table 5.1: Project Analysis Summary for GDi Fuel Injector Seat Machining

	EDM C'Bore / Spray Hole	Mill C'Bore / Laser Drill Spray Hole		
	Baseline	Start of Project (FY13Q1)	End of Project (FY16Q2)	Projected
# of Machines / Automation Modules	1 / 0	2 / 1	2 / 1	1 / 0
Work Holding	Threaded Collet	5 Piece Collet - 3 Jaw Chuck	1 Piece Collet - 3 Jaw Chuck	Colletless Chuck
Cycle Time (sec)	105	30	21	14
Power Consumption (kW)	4.1	6.6	6.6	3.8

Figure 5.2 shows year-by-year estimates of annual energy consumption benefits for this project. Results from three LIGHTenUP calculations are provided based on EDM manufacturing, Delphi laser manufacturing at the beginning of the project, and Delphi advanced laser manufacturing at the end of the project (current). All manufacturing methods considered individually show a substantial increase in energy consumption with time. This is a result of Delphi manufacturing an increasing number of fuel injector nozzle seats each year as the number of GDi vehicles grows (recall previous discussion of Figure 5.1).

Figure 5.2: Comparison of Estimated Delphi Annual Energy Consumption Rates for GDi Fuel Injector Seat Machining

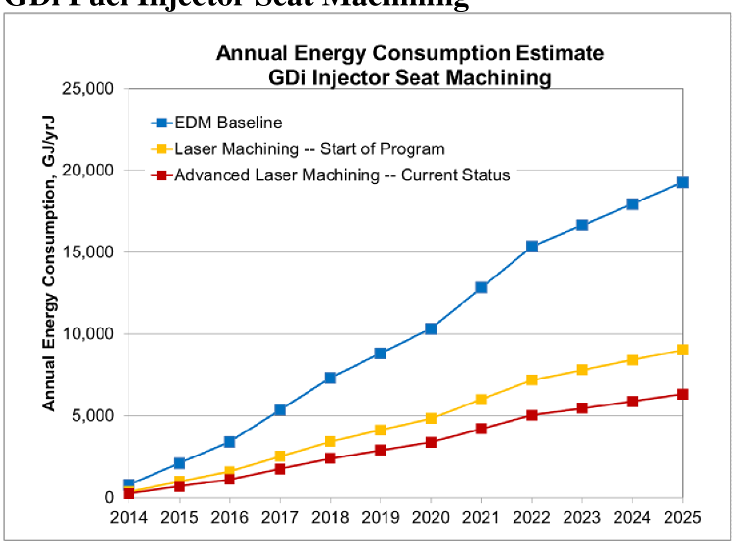
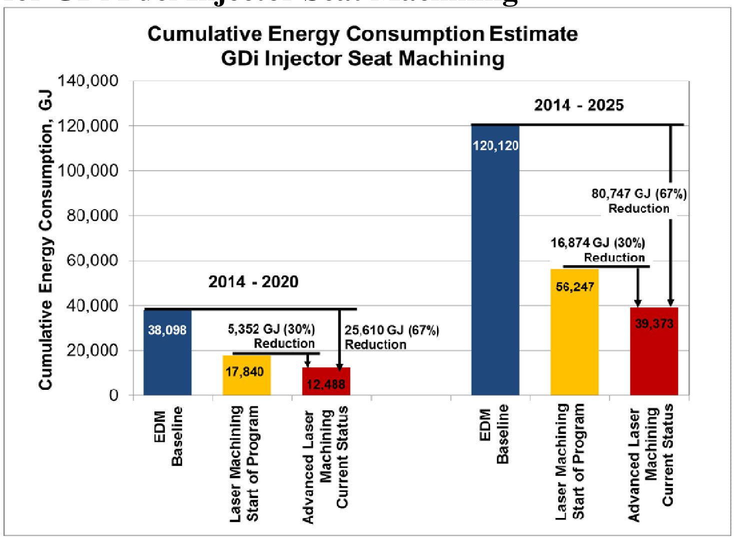


Figure 5.3 provides cumulative estimates of energy consumption. Represented are estimates of cumulative consumption from 2014–2020 (LHS of the figure) and from 2014–2025 (RHS of the figure). Delphi estimates the advanced laser method in its current status (end of project) provides a 67% reduction in energy consumption compared to the EDM baseline and

a 30% reduction compared to the Delphi laser manufacturing process as it existed at the beginning of the project. Quantitatively, current status advanced laser manufacturing compared to EDM results in an estimated 25.6 TJ (2.4E^{-2} TBTU) reduction through 2020 and an 80.7 TJ (7.6E^{-2} TBTU) reduction through 2025.

Figure 5.3: Comparison of Estimated Delphi Cumulative Energy Consumption Rates for GDi Fuel Injector Seat Machining



With respect to environmental benefits, Delphi estimates the reduction in energy consumption described above results in a decrease in CO_2 emissions by 67% for the current status advanced laser manufacturing compared to EDM. Additionally, the ability to eliminate surface cleaning or etching processes (i.e. post processing) due to the high precision machining capabilities reduces the use of toxic chemicals such as acid baths.

ENVIRONMENTAL AND ENERGY BENEFITS (Microlution): The applications addressed in Budget Period 2 of the project represent an expansion of the scope of the project due to achieving the goals related to the GDi application during Budget Period 1. As a result, any energy savings achieved during Budget Period 2 will be in excess of those targeted for the original goal of the project.

The applications considered during Budget Period 2 include Precious Metal Drilling for Cardiac Catheter Devices, Ceramic Hole Drilling for Probe Cards, Precious Metal Cutting and Measuring of Marker Bands, and Hybrid Machining for Test Sockets. These applications currently use a range of manufacturing processes including EDM and various types of mechanical cutting. Similar to Budget Period 1, the expected processing time for each of these applications using ultrafast laser technology is lower than the competing manufacturing technology. Also, as with EDM versus ultrafast laser technology, the energy consumption per machine tool is estimated to be lower with ultrafast laser technology versus the competing technology. Therefore, Microlution estimates that using ultrafast laser technology will deliver a manufacturing energy savings for each of these applications. In order to determine the total amount of energy savings, Microlution needs to understand the market penetration of ultrafast laser technology for each of these applications. However, estimating the market penetration is not possible at this time since Microlution is only at the phase of demonstrating proof-of-capability for each of these applications. As Microlution's commercialization efforts continue and insight is gained into market penetration, it will be possible to understand the associated energy savings.

CYCLE TIME IMPROVEMENT (Delphi): Cycle times for the different processes are shown in Table 5.1. Delphi estimates the advanced laser method in its current status (end of project) provides an 80% reduction in cycle time compared to the EDM baseline and a 30% reduction compared to the Delphi laser manufacturing process as it existed at the beginning of the project. Quantitatively, current status advanced laser manufacturing compared to EDM results in an estimated 84 second reduction in cycle time. Additionally, improved precision reduces re-work and scrap rates, and eliminates the need for secondary processes such as etching, surface cleaning, and/or deburring.

CYCLE TIME IMPROVEMENT (Microlution): Cycle times for the different applications are shown in Table 5.2. For several of the applications that were explored in Budget Period 2, significant cycle time improvements were realized compared to the target values. The target values were determined based on estimated cycle times for competitive technologies, also factoring other costs such as capital equipment, disposable tooling, etc. The values that were determined constitute times that make the technology that was developed a viable competitive option for the application. Each of the applications focused on replacing a different competitive technology or making an improvement to a process where there was not an existing technology that offered a viable alternative.

Table 5.2: Comparison of Cycle Time Improvements for Applications Explored by Microlution

	Subtask			
	6.1 Multi-Axis High/Low Frequency Coordination	7.1 Precious Metal Drilling for Cardiac Catheter Devices	7.2 Ceramic Hole Drilling for Probe Cards	8.1 In-Situ Measurement for Laser Tube Processing for Marker Bands
Target Cycle Time	1.5	3	10	2
Actual Cycle Time	0.7	1.7	3.1	1.2

Subtask 6.1 explored the use of a new control technology to realize the cycle time reduction. The use of galvo motors to control mirrors in synchronization with linear motors offers a significant speed improvement for specific types of applications as opposed to using linear motors or galvo motors alone. A cycle time reduction of greater than 50% was realized for the multi-axis high/low frequency coordination application.

Precious metal drilling for cardiac catheter devices is a process that has traditionally been performed by EDM. Therefore, by implementing ultrafast laser technology, the gains that can be realized in this market segment are very similar to those already achieved by Delphi with fuel injector nozzle seats. For the specific application that was explored in Subtask 7.1, a cycle time improvement of more than 40% was realized over the target value.

Ceramic hole drilling for probe cards is traditionally an application for high-speed mechanical drilling. However, geometry limitations and high tooling costs make this an ideal application for ultrafast laser processing. The cycle time for this application was almost 70% below the target.

The process for marker band fabrication has traditionally been a mechanical cutting process. This results in high tooling and post processing costs. Based on market analysis, a target cycle time of 2 seconds was determined to make ultrafast laser processing a viable alternative to the traditional method. For the specific application that was explored, a cycle time was achieved that was 40% below the target value. It is important to note that this was just one sample application. Marker bands come in a wide variety of sizes and ultrafast laser may not be the right technology of all types of marker bands. However, this does show that ultrafast laser technology is viable for this market segment.

6. Commercialization

The development team pooled market analysis data and formulated commercialization plans. These plans will be executed primarily by Microlution, since Delphi is not in the machine tool market. During Budget Period 2, Coherent Inc. purchased the assets of Raydiance, so the Final Scientific/Technical Report will not include any market analysis findings and data or commercialization plans from Raydiance.

This successful project enables widespread deployment of the developed micromachining method. Delphi identified the technology need. The technology was developed with the assistance of Microlution for an automotive application. Delphi was highly motivated after the completion of Budget Period 1 to deploy the technology as a mainstream manufacturing method for fuel injectors for its global customer base as well as for other areas of its product portfolio. Microlution then used the developed technology to expand to other applications.

The technical capability enabled by ultrafast laser cutting is compelling from a pure quality and feature-generation-capability perspective in a broad range of applications. For this technology to be successfully commercialized, it must also have an overall cost benefit compared with competing manufacturing technologies. In the case of the other applications developed during Budget Period 2, the primary factors associated with manufacturing costs are:

- System capital costs (i.e. the cost of the machine)
- System operating costs
    - Cycle time / throughput
    - Energy (primarily electricity and compressed air)
    - Consumables (i.e. disposable cutting tools, process fluids and gas, filters, etc.)
    - Manufacturing floor space
    - System utilization and uptime
- System effect on up-stream and down-stream processes
    - Material handling costs
    - Measurement and inspection requirements

The effort in Budget Period 2 focused not only on developing the fundamental processing capability, but also on improving the overall manufacturing cost associated with laser processing systems. The multi-application testbed system development work focused on reducing cycle time, energy use, and manufacturing floor space while maximizing laser utilization, improving material handling efficiency, and optimizing measurement and quality control processes. The commercialization effort is directly leveraging these improvements, enabling manufacturing systems that deliver a competitive cost advantage over existing technologies. As Microlution continues to move forward with commercialization efforts they will also continue development efforts to provide further improvements in the system capital cost, operating costs, and effect on related processes.

Microlution is a growing company that supplies their products to manufacturers over a broad range of industries. Based on Microlution's continued technical development plan and their understanding of customer needs and cost structures, they believe the technology developed as a part of this project will succeed in the market. In fact, active sales conversations are currently benefitting from this technology and Microlution expects they will result in sales in the near term.

7. Accomplishments

a) Subtask 1.1: Demonstrated the laser scan head performing with a rotational speed > 200Hz at an attack angle > 80%.
b) Subtask 1.2: Demonstrated through hole laser drilling in fuel injector nozzle seats in 50% less time than the current system with no degradation in quality.
c) Subtask 1.3: Demonstrated laser drilled fuel injector nozzle spray holes and counterbores in stainless steel coupons in < 8 seconds.
d) Subtask 2.1: Delivered a work holding concept selection matrix and test plan.
e) Subtask 2.2: Delivered a report summarizing work holding test results, data, and concept recommendation.
f) Subtask 3.1: Demonstrated and performance tested the enhanced laser chassis with a load and unload time to work position in 2.9 seconds (using Load/Unload Test Station) and capability to synchronize movement during the laser firing sequence.
g) Subtask 3.2: Demonstrated and tested fully integrated ultrafast laser system with warm-up time to stability in < 15 minutes and measurement of counterbore depth and diameter at programmable intervals.
h) Subtask 4.1: Demonstrated system producing fuel injector nozzle seats using optimized process parameters.
i) Subtask 4.2: Demonstrated system producing fuel injector nozzle seats which fulfill customer requirements for a specific application.
j) Subtask 5.1: Designed a testbed system (application platform) that was used to develop and prove production processes for the identified electronic and biomedical industrial applications. Demonstrated that the testbed design met or exceeded the measureable performance criteria
k) Subtask 5.2: Built and tested a testbed system that provides an application platform used to develop and prove production processes for the identified electronic and biomedical industrial applications. Demonstrated that the testbed system met or exceeded the measureable performance criteria.
l) Subtask 6.1: Demonstrated the ability to separate 5-axis trajectory into high frequency/low frequency components, executed motion on the testbed, and achieved the desired machining result.
m) Subtask 7.1: Used the testbed to demonstrate the ability to produce typical precious-metal holes for cardiac catheter devices with dimensions of 0.075mm diameter, 0.450mm depth and, less than 2 degree taper with a process cycle time of 3 seconds or less.
n) Subtask 7.2: Used the testbed to demonstrate the ability to produce standard probe-card holes with dimensions of 0.075mm diameter, 0.650mm depth, and less than 2 degree taper with a process cycle time of 10 seconds or less.
o) Subtask 8.1: Used the testbed to simultaneously cut and measure a tube with a 0.500mm diameter, a 0.050mm wall thickness, and a 0.500mm part length to 0.01mm accuracy with a process cycle time of 2 seconds or less.
p) Subtask 8.2: Used the testbed to demonstrate the ability to produce milled and ultrafast laser machined features with a positional tolerance of ±0.012mm relative to each other on a representative test-socket part. The milled feature was a 1.100mm deep by 0.241mm diameter hole and the laser cut feature was a slot that met the dimensional requirements of 0.051±0.009mm wide by 0.129±0.006mm long by 0.100mm thru.

8. Conclusions

The techno-economic issues for this manufacturing method are rooted in the potential for substantial increases in machining precision and reduced cycle times with the laser-based techniques. The increased speed, reduced scrap rate, and reduced need for consumable tools will lead to substantial reductions in energy consumption and manufacturing costs.

For the Delphi fuel injection application, the market need for improved micromachining capability is clear. Recently-announced legislation requiring reduced vehicle CO_2 emissions and improved fuel economy is leading to greater complexity in the flow and spray characteristics required for next-generation engines. Delphi already has customers in place and continues to win future business to deliver injection systems that meet these stringent requirements. Ultrafast laser-based micromachining offers a potential game-changing technology to manufacture injectors for these systems. The advancements in this project were developed in parallel with work to upgrade conventional manufacturing methods (performed outside the scope of this project). Delphi was able to validate and deploy the developed processes to deliver products to existing customers worldwide.

Microlution will leverage the technology advances gained from this project to deploy the technology to a broader customer base. The multi-application testbed developed can be utilized by potential markets in a wide variety of industries beyond automotive, due to the varied machining capabilities of the ultrafast laser such as the examples below:

- Hole drilling (fuel injectors, turbine blades, cell phones, medical devices)
- Deep engraving (printing dies, industrial tools)
- Scribing (displays, solar cells, LED wafers, Si wafers)
- Cutting (medical devices, cell phones, laptop computers)
- Surface marking and texturing (turbine blades, impellers)

The technology advances for Microlution have already resulted in machine sales into the new application areas for ultrafast laser drilling and cutting as well as hybrid machining and measuring operations that include ultrafast lasers. The application areas where sales have been achieved include 1) biomedical devices involving precious metal drilling, 2) biomedical devices involving hybrid laser cutting and measuring, and 3) consumer electronics devices involving ceramic hole drilling. Microlution expects to achieve continued penetration and to win machine sales in these applications as well as the others pursued as part of this project.

9. Recommendations

There are no commercialization path recommendations as entry into production is immediate.

10. References and/or Bibliography

[i] "Decision-matrix method." *Wikipedia: The Free Encyclopedia*. Wikimedia Foundation, Inc., last modified on 25 September 2013. Web. 16 January 2014. <http://en.wikipedia.org/wiki/Decision-matrix_method>

[ii] "Process capability index." *Wikipedia: The Free Encyclopedia*. Wikimedia Foundation, Inc., last modified on 15 March 2014. Web. 26 March 2014. <http://en.wikipedia.org/wiki/Process_capability_index>

11. Appendices

Appendice 11.1: Task Schedule

Task #	Subtask #	Task Title or Brief Description	Responsible Party	Task Completion Date			
				Original Planned	Revised Planned	Actual Complete	% Complete
1.0		**Laser and Scan Head Development**	**Raydiance**	**Fri 8/16/13**	**Mon 12/16/13**	**Mon 12/16/13**	**100%**
	1.1	Develop Workstation Design and Build		Fri 2/1/13	Mon 7/8/13	Mon 7/8/13	100%
	1.2	Material Removal		Fri 8/16/13	Mon 12/16/13	Mon 12/16/13	100%
	1.3	Counterbore Process Development		Fri 6/7/13	Mon 12/16/13	Mon 12/16/13	100%
2.0		**Work Holding and Automation**	**Delphi**	**Fri 6/21/13**	**Fri 1/31/14**	**Mon 3/17/14**	**100%**
	2.1	Develop Work Holding Concept and Datum Structure		Fri 2/15/13	Fri 4/26/13	Fri 4/26/13	100%
	2.2	Automated Work Holding Demonstration		Fri 6/21/13	Fri 1/31/14	Mon 3/17/14	100%
3.0		**Laser and Scan Head Chassis Development**	**Microlution**	**Fri 6/21/13**	**Fri 11/29/13**	**Wed 12/18/13**	**100%**
	3.1	Laser Chassis Development		Fri 5/10/13	Fri 9/13/13	Fri 9/27/13	100%
	3.2	Integration and Test		Fri 6/21/13	Fri 11/29/13	Wed 12/18/13	100%
4.0		**Optimization and Valve Seat Build**	**Delphi**	**Fri 10/4/13**	**Mon 3/31/14**	**Mon 3/17/14**	**100%**
	4.1	Integrated Component Processing		Fri 9/13/13	Tue 12/31/13	Wed 1/29/14	100%
	4.2	Develop Valve Seat		Fri 10/4/13	Mon 3/31/14	Mon 3/17/14	100%
5.0		**Multi-Application Testbed Development**	**Microlution**	**Thu 7/2/15**	**Fri 10/30/15**	**Fri 12/18/15**	**100%**
	5.1	Design Multi-Application Testbed		Fri 1/30/15		Fri 1/30/15	100%
	5.2	Build and Test Multi-Application Testbed		Thu 7/2/15	Fri 10/30/15	Fri 12/18/15	100%
6.0		**Advanced Control Development for Coordinated Motion and Laser Firing**	**Microlution**	**Fri 10/30/15**	**Thu 3/31/16**	**Thu 3/31/16**	**100%**
	6.1	Multi-Axis High/Low Frequency Coordination		Fri 10/30/15	Thu 3/31/16	Thu 3/31/16	100%
7.0		**Laser Processing Strategy Development**	**Microlution**	**Fri 7/31/15**	**Thu 3/31/16**	**Mon 2/22/16**	**100%**
	7.1	Precious Metal Drilling for Cardiac Catheter Devices		Fri 5/1/15	Thu 3/31/16	Mon 2/22/16	100%
	7.2	Ceramic Hole Drilling for Probe Cards		Fri 7/31/15	Fri 10/30/15	Thu 12/31/15	100%
8.0		**Hybrid Machining Strategy Development**	**Microlution**	**Thu 12/31/15**	**Thu 3/31/16**	**Wed 3/9/16**	**100%**
	8.1	In-Situ Measurement for Laser Tube Processing for Marker Bands		Fri 10/30/15	Thu 3/31/16	Fri 2/19/16	100%
	8.2	Hybrid Machining for Test Sockets		Thu 12/31/15	Thu 3/31/16	Wed 3/9/16	100%
9.0		**Project Management and Reporting**	**Delphi & ML**	**Fri 8/29/14**	**Wed 6/29/16**	**Wed 6/29/16**	**100%**
	9.1	Progress / Technical and Financial Reporting		Fri 8/29/14	Wed 6/29/16	Wed 6/29/16	100%
	9.2	Attend Department of Energy (DOE) Project Kick-Off and Review Meetings		Fri 8/29/14	Thu 3/31/16	Fri 3/25/16	100%
	9.3	Market, Environmental, and Energy Benefit Analysis		Fri 8/29/14	Wed 6/29/16	Wed 6/29/16	100%
	9.4	Commercialization Initiatives		Fri 8/29/14	Wed 6/29/16	Wed 6/29/16	100%

Appendice 11.2: Milestone Schedule

Milestone Title or Brief Description	Milestone Completion Date			
	Original Planned	Revised Planned	Actual Complete	% Complete
Demonstrate scanning head meets or exceeds performance targets	Fri 2/1/13	Mon 7/8/13	Mon 7/8/13	100%
Demonstrate 50% CT reduction for laser drilling through holes	Fri 8/16/13		Mon 7/8/13	100%
Laser drill c-bore and spray hole < 8 seconds and pass spray criteria	Fri 6/7/13	Mon 12/16/13	Mon 12/16/13	100%
Present concept selection matrix, tool trial data, and results summary	Fri 6/21/13	Fri 1/31/14	Mon 3/17/14	100%
Demonstrate enhanced laser chassis meets or exceeds performance targets	Fri 6/21/13	Mon 9/30/13	Fri 9/27/13	100%
Utilize enhanced laser chassis to develop a seat for a specific customer application	Fri 10/4/13	Mon 3/31/14	Mon 3/17/14	100%
DOE agrees to proceed into Budget Period 2 (Go/No-Go Decision Point)	Sat 8/31/13	Mon 3/31/14	Thu 11/6/14	Y
Demonstrate testbed design meets or exceeds performance criteria	Fri 1/30/15		Fri 1/30/15	100%
Demonstrate testbed system meets or exceeds performance criteria	Thu 7/2/15	Fri 10/30/15	Fri 12/18/15	100%
Demonstrate advanced control with multi-axis high/low frequency coordination	Fri 10/30/15	Thu 3/31/16	Thu 3/31/16	100%
Demonstrate precious metal drilling performance	Fri 5/1/15	Thu 3/31/16	Mon 2/22/16	100%
Demonstrate ceramic hole drilling performance	Fri 7/31/15	Fri 10/30/15	Thu 12/31/15	100%
Demonstrate tube cutting process	Fri 10/30/15	Thu 3/31/16	Fri 2/19/16	100%
Demonstrate hybrid machining of test sockets	Thu 12/31/15	Thu 3/31/16	Wed 3/9/16	100%
Quarterly Research Performance Progress Reports	Wed 10/31/12	Sat 4/30/16	Fri 4/29/16	100%
Continuation Application - 1st submission	Fri 5/31/13	Mon 9/30/13	Mon 9/30/13	100%
Continuation Application - 2nd submission	Sat 8/31/13	Tue 1/7/14	Tue 1/7/14	100%
Continuation Application - 3rd submission	Mon 3/31/14		Wed 3/26/14	100%
Final Scientific/Technical Report	Fri 11/28/14	Wed 6/29/16	Wed 6/29/16	100%
DOE project kick-off meeting	Thu 11/29/12		Thu 11/29/12	100%

Appendice 11.3: Project Spend Plan

Federal Fiscal Year & Quarter	From	To	Estimated Federal Share of Outlays	Actual Federal Share of Outlays	Estimated Recipient Share (Cost Share) of Outlays	Actual Recipient Share (Cost Share) of Outlays	Cumulative Estimated Outlays (Federal + Recipient)	Cumulative Actual Outlays (Federal + Recipient)
	Start	9/30/12	Note 1	$215,454	Note 1	$53,863	Note 1	$269,317
FY13Q1	10/1/12	12/31/12	$0	$128,998	$0	$32,250	$0	$430,565
FY13Q2	1/1/13	3/31/13	$0	$381,090	$0	$95,273	$0	$906,928
FY13Q3	4/1/13	6/30/13	$0	$319,710	$0	$79,928	$0	$1,306,566
FY13Q4	7/1/13	9/30/13	$0	$668,193	$0	$167,048	$0	$2,141,807
FY14Q1	10/1/13	12/31/13	$0	$451,192	$0	$112,798	$0	$2,705,797
FY14Q2	1/1/14	3/31/14	$0	$369,931	$0	$92,483	$0	$3,168,211
FY14Q3	4/1/14	6/30/14	$0	$0	$0	$0	$0	$3,168,211
FY14Q4	7/1/14	9/30/14	$0	$0	$0	$0	$0	$3,168,211
FY15Q1	10/1/14	12/31/14	$0	$52,441	$0	$15,962	$0	$3,236,614
FY15Q2	1/1/15	3/31/15	$0	$400,553	$0	$102,654	$0	$3,739,821
FY15Q3	4/1/15	6/30/15	$0	$356,243	$0	$91,298	$0	$4,187,362
FY15Q4	7/1/15	9/30/15	$0	$209,412	$0	$53,669	$0	$4,450,443
FY16Q1	10/1/15	12/31/15	$0	$134,473	$0	$34,463	$0	$4,619,379
FY16Q2	1/1/16	3/31/16	$0	$12,309	$0	$1,153	$0	$4,632,841
FY16Q3	4/1/16	6/30/16	$0	$0	$0	$0	$0	$4,632,841
Totals			$0	$3,700,000	$0	$932,841	$0	$4,632,841
Approved Budget			$3,700,000		$932,841		$4,632,841	

Note 1: Leave blank. Only the actual DOE/Cost Share amounts spent are needed.