<u>I & I Final Report</u>

A HOTEYE™-BASED COORDINATE MEASURING MACHINE FOR THE FORGING INDUSTRY

By

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DOE GRANT NO.
DE-FG36-01GO11033

Submitted on: April 30, 2003

I. SUMMARY OF ORIGINAL PROJECT GOALS

The objective of this project is to develop a 3 dimensional measurement system for the domestic forging industry based on HotEye™. This technology will allow high definition camera to accurately image a red hot object. The project marries conventional Coordinate Measurement Machine "CMM" technology to HotEye™ technology to permit the accurate measurement of forged parts while they are at high temperature. Being able to take such measurements will dramatically reduce the amount of scrap produced by the domestic forging industry. This industry wastes a significant amount of energy because of the high rate of scrap it produces. OGT will:

- Develop a 3D measurement sensor head that will work on a part at a temperature up to 1,450°C with an accuracy of 0.1mm or better and with a scanning speed of less than 10 seconds for an area of 100mm x 100mm.
- Develop a Virtual-Fixturing software package to alleviate the need of precise hard fixturing.
- Integrate the 3D measurement sensor head and the Virtual-Fixturing software into a standard CMM, both hardware (replacing the probes) and software (data format and user interface match) so that the system can automatically perform a complete pre-programmed measurement of a hot product.
- Test and evaluate the system in a forging facility.

II. VARIANCE FROM PROJECT GOALS

The project goals are basically well maintained with three deviations.

First, the scanning area is 80 mm x 120 mm, instead of the intended 100 mm x 100 mm. This is due to the format of the imaging sensor we used. These sensors are rectangular, instead of square. The prototype system is capable of achieving the original goal to scan an area of 80 mm x 120 mm (approximately the same coverage of 100 mm x 100 mm) within 10 seconds.

Second, the steepest slope on the part surface to be measured is limited to 35°. This is the limit of a vision system, which is working based on "line of sight." Any surface that is obscured or heavily distorted can not be measured accurately through vision technology. This limit can be address by adding the 4^{th} axis, a rotating axis, to the CMM. The 4^{th} axis is very common in the conventional CMMs, in which the touch probes are tilted to access the part dimensions. Nevertheless, all vision based CMMs, such as those supplied by OGP, Nikon and Microview, are all equipped with 3 axes, as was planned in this project.

Third, the business goal goes beyond the "CMM" scope. Applications have been identified for the HotEye™ 3D module, an essential portion of this development project.

III. DISCUSSION ON PROJECT RESULTS

The project results are very encouraging. Technical goals are 100% accomplished. Nevertheless, additional work is necessary for the HotEye™ CMM to be fully commercialized and OGT is committed to complete it.

Goal#1: Develop a 3D measurement sensor head that will work on a part at a temperature up to 1,450℃ with an accuracy of 0.1mm or better and with a scanning speed of less than 10 seconds for an area of 100mm x 100mm.

During this project period, a 3D measurement sensor head was developed, as shown in Figure 1. HotEye™ based 3D sensor head.. This sensor head was tested in OGT or in TECT and on both hot and cold targets, as illustrated in Figure 2.

It is proved that the sensor head is capable of scanning an area of 80 mm x 120 mm within 10 seconds. Also, the sensor head is tested for the capability of scanning an object that is as hot as 1,500°C.

The accuracy is verified with a known geometric surface: an optical flat. This optical flat is flat to 1/10 of a wavelength (green light), or ~55 nm. This optical flat was set in different attitudes (tilting angles 0 to 35° in both X and Y directions) for the accuracy tests. Accuracy is defined as the ability of the 3D sensor head to measure and reconstruct the flat surface, even if the flat surface is positioned freely (any attitude with tilt angles less than 35°) in the 3D space. The results are shown in Figure 3 and Figure 4. Overall, the 3D sensor head is achieving the goal of 0.1 mm accuracy or better. It is interesting to observe that (a) there is a best tilt angle that yields the best accuracy, and (b) the accuracy is better (50% improvement) in TECT than in OGT.

The best tilt angle can probably be explained by the "stereo observing angle." The stereo observing angle, as can be seen in Figure 1, is the angle between the observing device (imaging sensors in this case) and the measurement light ray. It was set to be 15° in this system design. The "best tilt angle" is around the area of 15 to 25°. Additional analysis is needed to further explain this trend.

The accuracy as tested in TECT (shop floor) is 2X better than that obtained by tests in OGT (lab). OGT attributes the improvement to a better calibration procedure and a better calibration tool. OGT deviated the project execution plan, as reported in the semi-annual reports and in the monthly invoicing reports, to develop an automatic calibration procedure for the prototype system.

Goal#2: Develop a Virtual-Fixturing software package to alleviate the need of precise hard fixturing.

The prototype, shown in Figure 5, is only equipped with a very simple and inaccurate hardware fixture (Figure 6). The software is capable of measuring the surface profile of the part and adjusting the attitude of the part for the needs of getting the exact perspectives. Figure 7 illustrates the capability of the prototype system in performing "virtual fixturing."

Goal#3: Integrate the 3D measurement sensor head and the Virtual-Fixturing software into a standard CMM, both hardware (replacing the probes) and software (data format and user interface match) so that the system can automatically perform a complete pre-programmed measurement of a hot product.

The 3D measurement sensor head and the software were integrated into a CMM form system, as shown in Figure 8. It is capable of measuring a hot product, at the specification in accordance with those described in Goal#1.

Goal#4: Test and evaluate the system in a forging facility.

The prototype was tested and evaluated in the shop floor of TECT for more than 3 months. During the period, the accuracy of the prototype was evaluated twice. Evidence has shown that the system can sustain the forging shop floor environment and maintain its accuracy. Furthermore, the system was tested on both cold turbine blades and hot turbine blades. The system was used to measure the blade surface profile dimensions as soon as the blades leave the trim press, the final stage of the forging process. TECT personnel were trained to operate the prototype to ensure the user-friendliness of the prototype system.

In addition to the tests and evaluation, the prototype was showcased to the audience of the Forging Industry Technical Conference, hosted in Cleveland, Ohio with a plant tour to TECT (Figure 9). The prototype testing was part of the interview given by TECT to the *Forging Magazine*, published in the January/February issue.

OGT and TECT together even go beyond the planned test. OGT is attempting the matching of the measured data cloud to the blade CAD model. To support this additional test, the prototype system is still being kept in TECT as the project ended.

IV. COMPLETED MILESTONE TABLE

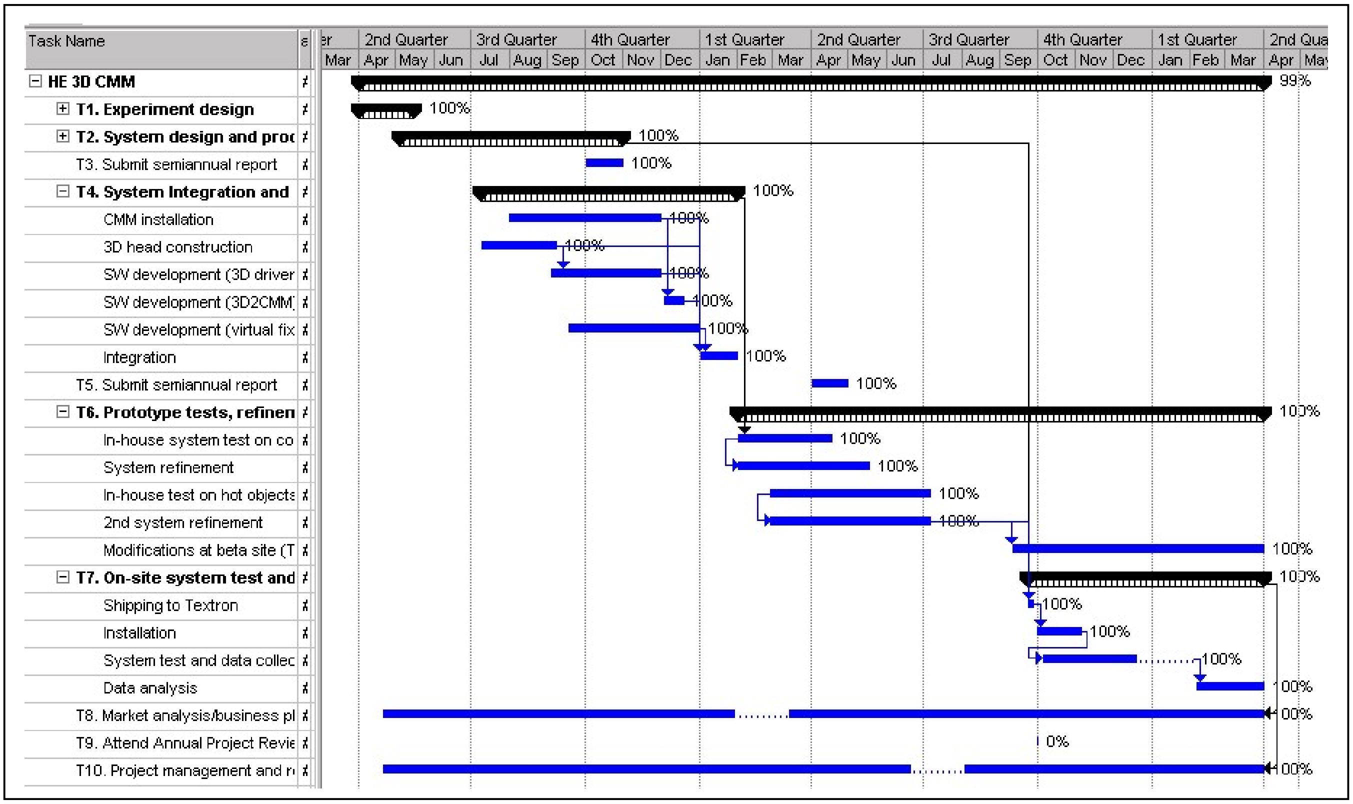
The completed milestone table is as following.

	Milestone/ Task Title	Completion Date			Responsible Organization	Cost (Fed/Non-Fed)			Milestone Notes
		Original Planned	Revised Planned	Actual		Original Projected	Revised Projected	Actual	
1	Experiment Design	4/30 2001		5/15 2001	OGT	$5,012 / $524		$3,868 / $557	
2	System Design and Procurement	8/31 2001		10/31 2001	OGT	$73,272 / $164,152		$82,262 / $204,920	
3	Submit Semi-annual Report	10/31 2001		10/30 2001	OGT	Part of Task 10			
4	System Integration and Implementation	11/30 2001		1/31 2002	OGT	$16,375 / $1,727		$23,954 / $2,074	
5	Submit Semi-annual Report	4/30 2002		4/30 2002	OGT	Part of Task 10			
6	Prototype Tests, Refinement and Performance Analysis	9/30 2002	3/31 2003	3/31 2003	OGT TECT	$27,952 / $8,878		$35,268 / $9,487	
7	On-site System Test and Evaluation	9/30 2002	3/31 2003	3/31 2003	OGT TECT	$27,732 / $86,887		$11,317 / $112,081	
8	Market Analysis / Business Planning	9/30 2002	3/31 2003	3/31 2003	OGT	$28,972 / $964		$26,212 / $6,676	
9	Attend Annual Meeting	TBD			OGT	$935 / $100		$0/$0	Did not happen
10	Project Management and Submit Final Technical and Financial Status Reports	9/30 2002	3/31 2003	4/30 2003	OGT	$19,750 / $1,827		$17,119 / $1,840	

In this table, some costs are re-allocated to different tasks due to the extension of the project. There is an overspend of $72,576.00, primarily due to the extension of the project with the extended used of the HotEye™ sensors, the extended on-site test period and the extra labor to support the successful execution of the project. All the overspend is absorbed by OGT and TECT, in the form of cash and in-kind contribution.

V. FINAL GANTT CHART

The final Gantt Chart is as following.



VI. UPDATED ENERGY, WASTE AND ECONOMIC SAVINGS

The installed unit for the I&I project technology is HotEye™ based CMM and the associated 3D sensor head. The installed unit for the comparable competing technology as presented in the original proposal is hand tool such as calipers or similar gauges and conventional CMM. The significant difference is on the time shortened for the inspection of hot forged parts, instead of the energy consumption of the proposed units.

Energy Savings

The energy saving will be derived from the improved process efficiency by using the developed technology, as opposed to the competing technology. The developed technology is expected to improve the yield by 10%, based on the analysis in scrap reduction. This improvement can result in less use of energy and raw material (such as steel bars) proportionately in the forging industry.

The forging industry consumes more than 1.67 billion kWh of energy annually[1]. The updated addressable market size is 350 HotEye™ units (OGT's business plan), representing about 30% of the overall US forging industry (Forging Industry Statistics and OGT business plan). Therefore, the direct energy consumption by the addressable market sector is 500 million kWh per year. The direct energy savings, on average, can be derive by

500 million kWh (the total directly addressable energy) ***times*** *10% (scrap reduction)* ***divided by*** *350 (the expected number of HotEye™ units to deliver such improvement).*

The average direct energy saving per installation is expected to be 143K kWh/year/unit.

The developed technology has the potential to induce an indirect energy saving based on the reduced consumption of raw materials. For instance, it takes more than 5000 kWh on average to produce one ton of steel[2]. The domestic forging industry consumes ~15 million ton of steel bars annually[3] among which 11 million ton[4] is supplied by the domestic rolling industry. The total energy used to produce these bars is 44.7 billion kWh annually[5]. Only 30% (addressable market) will be affected by the developed technology, resulting in the amount of 13.4 billion kWh/year. The average indirect energy saving per installation can be derived

13.4 billion kWh (the total indirectly addressable energy) ***times*** *10% (raw material reduction)* ***divided by*** *350 (the expected number of HotEye™ units to deliver such improvement).*

This results in 3.83M kWh/year/unit for indirect energy saving.

Combined the expected average energy saving per unit is 3.97**M kWh/year/unit**, or **13.5B Btu/year/unit**.

According to the field survey, the energy consumption in the US forging industry is about 50% electricity and 50% natural gas. According to AISI[6], the US steel industry energy consumption is composed of 10% electricity, 30% natural gas and 60% coal.

Environmental Savings

The proposed technology does not reduce any emissions or releases. The scrap in the forging industry is typically recycled.

However, there is an average of 48 million tons of carbon equivalent emission for every 105 million tons of shipped steel[7]. Therefore, the raw material savings imply environmental savings. Based on 30% (addressable market) of the 11 million annual ship tons (domestic total volume), and the 10% reduction, there would be 330,000 tons of steel usage reduction. This will results in the reduction of carbon equivalent emission of 150,000 tons per year, or **430 tons/year/unit**.

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[1] Census, 1997.
[2] Energy Policy, American Iron and Steel Institute.
[3] Statistics, Forging Industry Association.
[4] Statistics, Forging Industry Association and American Iron and Steel Institute.
[5] Census, 1997.
[6] Energy Policy, American Iron and Steel Institute.
[7] Energy Use in the U.S. Steel Industry: An Historical Perspective and Future Opportunities, September 2000, Dr. John Stubbles, Energetics, Inc. prepared for U.S. Department of Energy, Office of Industrial Technologies

Economic Savings

The projected unit cost for the I&I project technology, when integrated into a commercial HotEye™ systems, was $200,000.

The comparable competing technologies such as hand tools are inexpensive, at the level of hundreds of dollars. However, the efficiency and accuracy of these competing technologies are way behind the I&I project technology.

Another comparable technology is the conventional CMM or conventional machine vision systems. The cost of these systems varies from $30,000 to $500,000. A system that is comparably capable is estimated to cost about $150,000. However, these systems will not work when the parts are hot.

Being able to measure and inspection the parts at high temperature with accuracy has a huge advantage. This will improve the forging process efficiency in the areas of scrap reduction, fast rampup after die changes, and longer die life. It is estimated the overall efficiency can be improved by 10% (details in OGT's business plan), which is huge for the forging industry.

The US forging industry has a sales volume of about $6 billion[8]. Assuming the same ratio, 30%, is used to identify the addressable market, this I&I project technology will impact the efficiency to delivery $1.8 billion worth of forged parts. A 10% increase in efficiency represents a $180 million increase in productivity, or $120 million reduction in cost[9]. It will take 350 HotEye™ units to deliver the improvement. Therefore, **the average unit benefit of the HotEye™ systems is $514,000/year/unit in productivity increase or $342,000/year/unit in cost reduction.**

The average return on investment for the HotEye™ systems would be at least 1.7X within one year. Or, the HotEye™ systems will be paid for by the economic benefits in 7 months.

VII. MARKET PENETRATION

There is <u>ONE</u> prototype of the HotEye™ based CMM being developed in this I&I project. This prototype has been tested and evaluated by TECT. This prototype is meeting the technical specification identified in the proposal. However, additional work is being continued by OGT and TECT to further enhance the functionality of the prototype. In this CMM prototype, there is a 3D sensing head embedded.

OGT has identified the industrial sectors that will be interested in the technology developed in this project. They are (1) the high-cost/low-volume forging sector and (2) the high-volume/low-cost precision forging sector. The former sector is the target for the developed prototype, the HotEye™ based CMM, which has a total US market size of ~30 units. The latter one, which has a total US market size of ~320 units, is the target for the 3D sensor head as developed in the course of this project.

OGT expects the 3D sensor head, as a product module, will be deployed into the target market faster than the HotEye™ based CMM because the 3D sensor head is in itself matured in this I&I project. The HotEye™ based CMM, though successfully implemented as a prototype, still needs additional integration work for commercial utilities. In fact, OGT has sold a HotEye™ system

[8] Forging Industry Association.

[9] Typical gross profit margin in the addressable market is 25 to 35%. We use 35% to estimate the cost for conservation.

with a 3D sensor head embedded to Metaldyne, the largest forging operation in the US. This HotEye™ system has passed off-line testing and is being install in-line for hot part inspection (Figure 10).

The domestic forging industry is a steady industry. However, the US forging industry is shifting from conventional forging to precision forging. The new investments are focused on the automatic precision forging lines, instead of the old drop forge lines. This trend is in favor of the developed technology. Therefore, OGT will project a conservative growth at 2% per year for the US market size.

OGT projects the market capturing as the following.

Category	U. S. Market				
	Project Completion Year	5 Years after Completion	10 Years after Completion	15 Years after Completion	20 Years after Completion
(A) Total number of units in U.S. market (addressable market)	350	380	410	450	490
(B) Total number installed unites using the technology (capturable market)	3	50	165	295	365
(C) Market penetration = B/A x 100%	1%	13%	40%	65%	75%

The rationales behind this projection are (1) the introduction of new sensing capability, (2) market adoption based on early business cases, (3) OGT's access to the US forging industry, and (3) market saturating after 75% penetration due to factors such as competition.

OGT at this moment does not expect competition from technologies at similar capability in the near term. By the time a new technology is developed, OGT would have established the market penetration.

VIII. COST SHARING SUMMARY

The cost share is summarized as following.

<u>#</u>	*<u>Company Name</u>*	*<u>Company Type</u>*	*<u>In-Kind Contribution</u>*	*<u>Cash Contribution</u>*	*<u>Total</u>*
1	OGT	Small business	$191,667	$19,452	$211,119
2	TECT	Small business	$126,516	$0	$126,516
	DOE		**$0**	**$200,000**	**$200,000**
	Total		**$318,183**	**$219,452**	**$537,635**

The cost share represents the following facts:

(1) OGT cost shared more than planned with additional $41,667 in in-kind and $$6,402 in cash.

(2) TECT cost shared more than planned with additional $24,507 in in-kind.

IX. PARTICIPANTS

The participants in this project include:

#	Company Contact	Address	City	ST	Zip	Phone/Fax/Email
1	Tzyy-Shuh Chang OGT	58 Parkland Plaza Suite 200	Ann Arbor	MI	48103	734-769-8500 / 734-769-1775 / chang@ogtechnologies.com
2	Haydn Garrett TECT	23555 Euclid Ave.	Cleveland	OH	44117	(216) 692-5558 / (216) 692-5665 / hgarrett@tectcorp.com

(1) OGT's roll is the project leader, the technology provider, and the technology commercialization entity. OGT was responsible for the overall execution of the project, reporting to DOE, design and develop the technology, integration of the technology into a prototype, data analysis and market assessment.

(2) TECT's roll is the customer of the developed technology. TECT assisted in the on-site test of the prototype system.

X. SUPPLEMENTAL INFORMATION

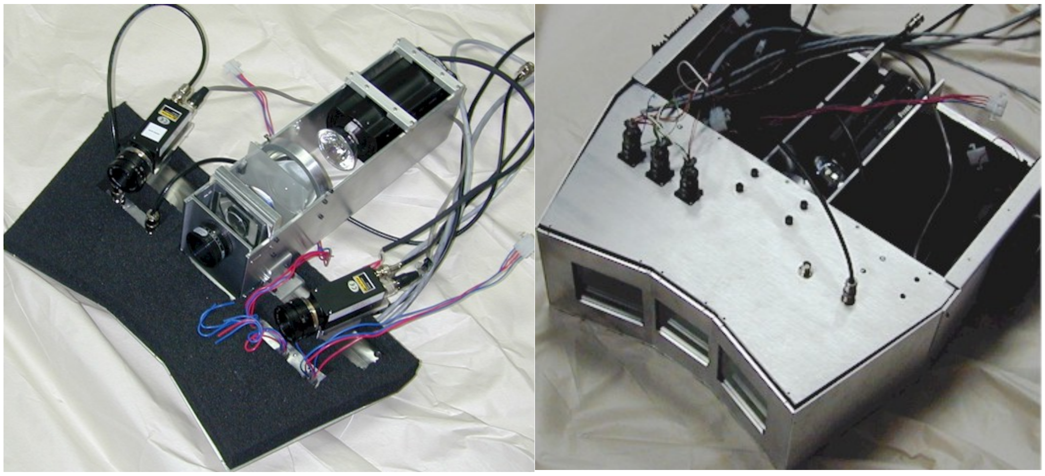

Figure 1. HotEye™ based 3D sensor head.

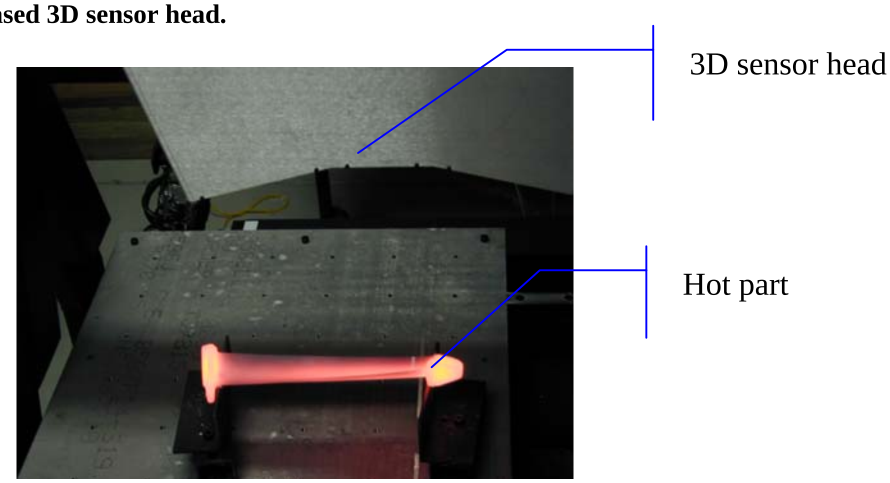

Figure 2. 3D sensor head tested with a hot part.

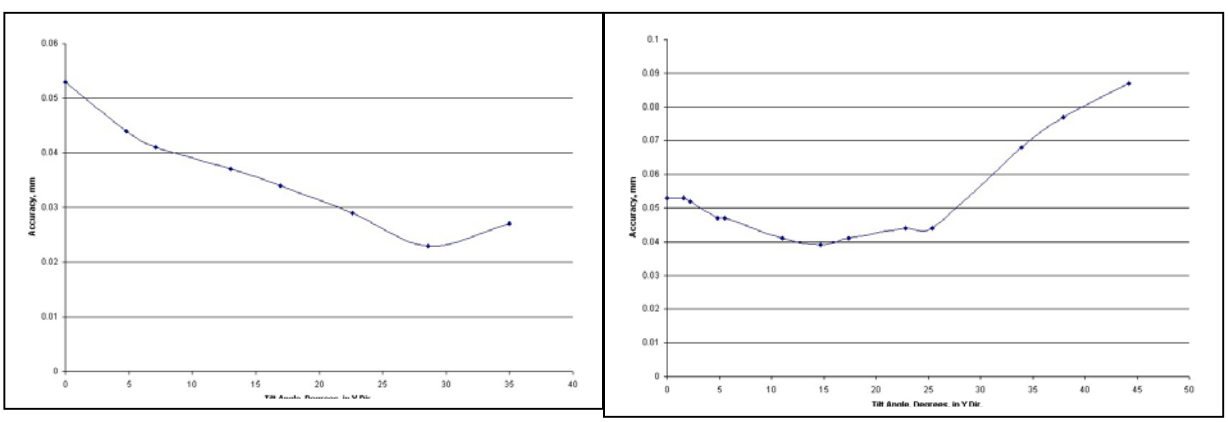

Figure 3. Accuracy data tested in OGT.

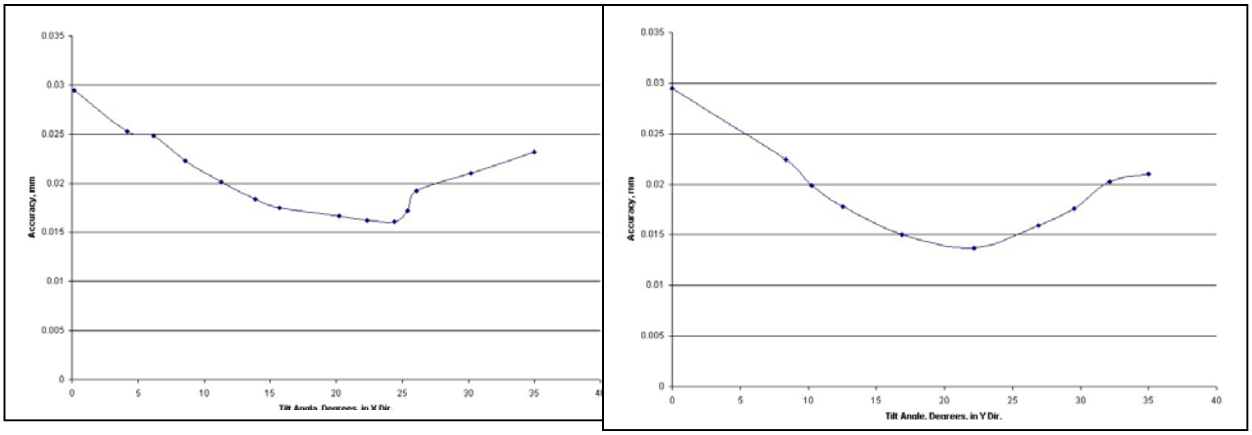

Figure 4. Accuracy data tested in TECT.

Figure 5. Prototype of the HotEye™ CMM system.

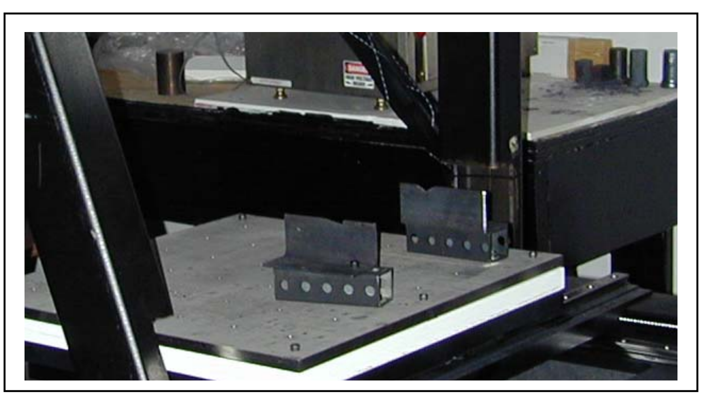

Figure 6. Hardware fixture in the prototype.

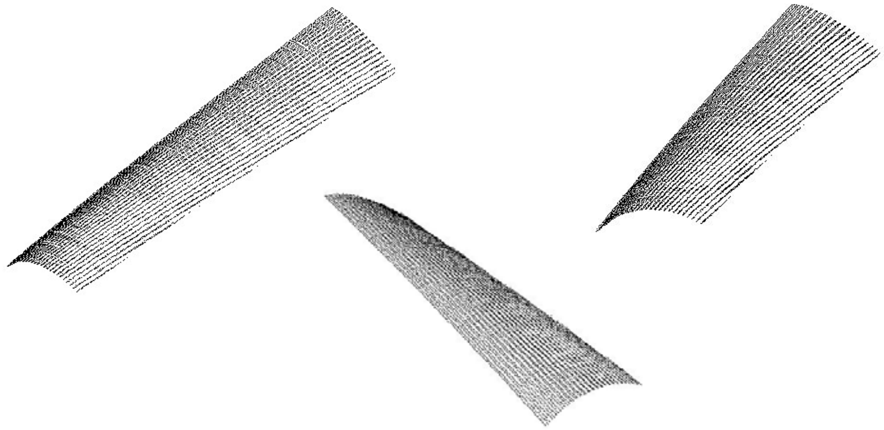

Figure 7. Data presented with different "virtual fixturing" settings.

Figure 8. Integrate HotEye™ CMM prototype.

Figure 9. The prototype system measuring a hot blade, showcased to FIA Technical Conference.

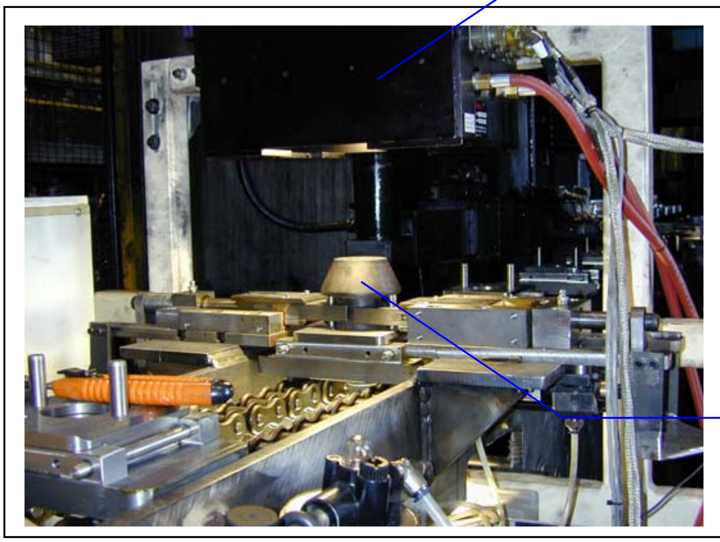

Figure 10. HotEye™ system in automatic stem pinion forging line.