Technology Innovations and Product Design Issues in Machine Vision
The Technical Arts Corporation Experience

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This paper discusses the distinction between technical innovations and product technologies. Technical innovations open new markets and spawn new industries. Product technologies must ultimately follow if these new breakthrough technologies are to ultimately evolve into mature product lines and the new industries survive and grow.

The experience of one company, Technical Arts Corporation, is used to illustrate how despite the closeness of the target markets to existing ones for their new products, the fruits of technical innovations often proved to be impediments to successful market penetration by their very success. The speed and accuracy of the new technology simply served to highlight the weakness of existing programming, maintenance, and operating systems and software. What used to be acceptable for these rather mundane aspects of computerized instrumentation no longer sufficed.

The basic scanning technologies developed by Technical Arts are described as are some of the subsequent product technology issues which needed addressing if the speed and accuracy of these techniques were to be realized. Through these and other innovations some of which are still in development, the transition from a technology company to a product company is taking place. This experience is probably typical of the machine vision industry as a whole.

In this paper we will discuss some of the issues faced by one company, Technical Arts Corporation (TAC), in it's particular machine vision niche; dimensional measurement. TAC has focused on this very narrow and, we feel, technologically conservative market area in order to minimize the exposure of the company to the combination of technological risk and the risks inherent in pioneering a new market.

In spite of this effort, substantial technological innovation has been required to bring TAC's products to maturity. We also envision the need for further innovations if TAC and other advanced technology companies are to continue to succeed in the field.

In a nutshell, the TAC experience with the introduction of its noncontact measurement systems into the industrial marketplace demonstrated that a small number of significant, even breakthrough, technological and product innovations is not sufficient to assure success. In order for the machine vision industry to finally achieve meaningful success in any market niche, a whole "market basket" of innovations and product concepts have to be successfully implemented. The technologies used must complement each other and be packaged in such a way as to bring real benefit to the customer, not simply more awesome wizardry or a handful of impressive specifications. Without this significant research and product development effort, the early machine vision products, including our own, were destined to fall significantly short of market acceptance.

We will discuss the pivotal technological innovation that launched TAC, high resolution structured light measurement. We will also discuss the subsequent efforts to both realize the ultimate promise of this technology (high accuracy) as well as some of the product technologies needed to make the technology of high speed measurement into a marketable product family. We will also touch upon our conjectures as to where our company is headed and what technological resources TAC, as well as others in the industry, will ultimately need.

Marketing as the Mother of Invention

Technical Arts originally developed process control algorithms for the wood and paper products industry. In the course of this business, a particular system, called a "trimmer", was being developed which basically looked for the bark area of the tree on cut (dimension) lumber. A certain amount of this barky — or wane — area is allowed, and we were designing a system to optimize the yield given

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BMVC 1990 doi:10.5244/C.4.1

the grading criteria.

The existing systems were slow, unreliable, and used primitive sensing technology. We made a fateful decision and told our clients that structured light, or the use of light sources and cameras to measure shape, could probably be successfully utilized to solve the wane measurement problem. Structured light involves the use of a plane of light, usually laser light, projected on some object for which one wishes a cross section. When a camera views this projection at some angle, the shape of the laser image uniquely determines the three dimensional shape of the cross section. Simple triangulation can be used to convert image information into dimensional data.

We sold a total of six scanners for the first system, each measuring six feet (1.8 meters) of lumber length. The total depth range of measurement of each scanner was about 20 feet (6 meters). What we failed to realize was that the task of detecting wane, which required locating the intersection of the wane, or bark, surface with the cut surface, routinely required resolution on the order of 0.004" (0.1 mm). The ratio of this dimensional depth resolution to the total measurable depth (ZFOV — or "Z" Field of View) was, therefore, 1 part in 60,000.

The cameras available to us had a maximum spatial resolution of no more than 1000 pixels. We were faced with the unenviable option of either unselling our customer on his original objective, or improving the spatial resolution of our basic system by at least one, if not two, orders of magnitude. Ultimately, we chose both.

After some rather spectacularly unsuccessful implementations, at least one of which we still hold a patent for [1], the method of locating the laser signal using the first moment of the intensity image was hit upon. We devised a digitizer which could, in real time, locate the signal on all camera lines and save this location information for further processing; a full resolution scanning rate of at least 15,000 measurements per second. This method, the "centroid" method, was implemented and did indeed provide resolution on the order of 1 part in 60,000 and repeatability in the 1:10,000 (1 sigma) range [2].

Recently, some evidence of the relative superiority of the centroid method for signal localization over such methods as zero crossing or peak detection has come to light [4]. In practice, the centroid method not only resulted in a substantial improvement in resolvable detail, it was remarkably robust in the presence of noise, low signal level, and nonlinearities such as those caused by surface features. It also was, in effect, perfectly linear; a 1 part in 10,000 shift of the laser pulse resulted in a 1 part in 10,000 change in the centroid value for all but the most egregiously abused signals (such as when oversaturated or swamped in ambient light). It was, it seemed, a godsend. What it was, we would soon discover, was an invitation to solve a whole range of other problems, if we were to proceed to try, as we did, to provide an instrument which not only could *resolve* detail to these heady levels, but also do so *accurately*. In other words, we wanted to be able to certify our dimensional data to precisions approaching our new found resolution specification. As the following discourse will show, achieving high resolution was only the first step toward the ultimate goal of measuring accurately.

From Resolution to Accuracy

While the original scanner (the 100) was developed in a spare bedroom with the help of two other part-time engineers, we realized that numerous other error sources needed to be addressed. We also knew that the digitizer could be gainfully employed to help us measure, and to some degree correct (or calibrate) some of these error sources and reduce their effect on accuracy. Although the complete list of measurable, and in some applications meaningful, error sources numbers at least a dozen [3] , a few of the more prominent follow:

- **Speckle.** Speckle is the interference pattern produced by a coherent source such as a laser when the light strikes an uneven surface. A very attractive sparkling pattern results, but this pattern is simply noise to the digitizer, rendering speckle a particularly obnoxious source of measurement error. We have worked with some very exotic techniques for reducing speckle over the years, all of which remind us that basic physical laws are generally hard to circumvent economically. Speckle error is proportional to the image beam width, inversely proportional to the laser wavelength, and is most pronounced in smaller field of view (higher precision) applications.

- **Lens Nonlinearity.** Camera lenses are not as precise (distortion free) as one would wish for in a measurement system; 1% errors are not unusual, and 0.1% accuracy is rare. We decided that, instead of pouring money into exotic optics for each scanner, we would invest in precise mapping of inexpensive lenses, using our high resolution digitizer, of course. In spite of the deceptively simple concept, lens mapping turned out to be a quite sophisticated process, especially in light of the minimum 0.012% tolerance we allow for a "shippable" lens. Lens nonlinearity is most pronounced on large field of view (low precision) systems, due to the wider lenses used and their relatively large distortions.

- **Laser and Mechanical Drift.** Lasers beams move, as do the mechanical contrivances which hold our components together and move them around. Temperature is the main culprit, and furious debate has raged in the measurement community as to the significance of thermal stability (if the part you're measuring is growing, why shouldn't the measurement machine grow too?). Laser drift is generally independent of ambient temperature, but is related to internal thermal effects in the package. It manifests itself in both short and long term pointing instability. Since precision machines are generaly compact, and large field of view systems generally have larger standoffs, laser and mechanical drift are usually an issue in all systems regardless of the size of the field of view (they scale).

- **Calibration.** Once a precise and reliable measurement is possible in the camera reference frame, it is necessary to translate these readings into similarly precise measurements in some known 3D spatial frame. This is a well known problem of finding the "projective transform", or a 4x3 nonlinear transform between the camera frame and the real world. If a carefully designed and manufactured gauge is placed in the scanner view, the known shape and the scan data of the gauge should render the transform information. In fact, this is true, although TAC has in recent years discovered that the simpler calibration methods are usually better than fully "automatic ", or "black-box", methods whereas in part scanning the opposite is generally true, as we shall discuss in the next section.

As the above items illustrate, the effects of different error sources impact different scanner configurations differently. In large field of view systems, lens linearity is more of an issue than speckle, while in high precision systems, the opposite is usually the case.

Ultimately we end up with accuracy of 1 part in 5,000 FOV (1 sigma) where we started with a resolution of over 1 part in 60,000. This substantial decrease is due more to the sheer number of error sources than the difficulty of correcting any one of them beyond a certain level. In any case, the best absolute accuracy achieved on a measurement system on the factory floor to date is 0.00025 inches (3 sigma).

This system, sometimes called the "White Scanner" has been very well received in the research community, due to the integrity of the data [5, 6]. The low noise on the scan data, particularly the absence of quantization, or pixel, noise results in certain forms of data analysis being significantly more reliable when compared to other sensor technologies.

Too Much of a Good Thing

Once the 100 series scanners were engineered to the point that the promise of high speed and accuracy was realized, it was generally assumed that that was good enough; that simply improving the throughput of existing metrological methods would, by itself, mean a ready market. Unfortunately, the reality was quite different. The very fact that the scanner produced literally thousands of measurements a second meant that no one, including TAC, knew exactly what to do with all that data. In fact, the relatively hefty investment required for the basic scanner meant that initially *only* customers who needed thousands of measurements beat a path to our door. The problem was; who wanted thousands of measurements on a printout? The obvious answer was; no one. Every customer wanted software which could process the hundreds or thousands of independent measurements per part and determine automatically the acceptability of the part being inspected.

This programming step, which determines what data to gather and how to analyze the results, is called "part programming". When only a few measurements were reasonably possible, such as with existing contact measurement technology, part programming was relatively simple (or non-existent). It usually involved setting up a few blocks, taking down a few readings, and pulling out a pad and calculator for the analysis step. The first major inspection system TAC built measured hundreds of points on an electronic part called a "lead frame". It took six man-months for us to write the part program for that machine. Immediately, it became clear that high speed measurement required more than simply providing certifiable accuracy — we needed to make speed an asset, not a bottom-line liability.

Certain tools were added to the scanner software to ease the part programming step, such as split-and-merge and cylinder segmentation [6], as well as a host of other regressions and mathematical routines. These low level routines helped the operator segment (or sort out between features on the part) the various scan data cross-sections [7]. These tools, although not high-level enough to be considered "artificial intelligence" applications, substantially reduced the data handling load of the applications programmer and brought the cost of part programming down by a factor of ten.

Model Based Measurement

A second side effect of the speed issue arose in spite of these efforts. Another realm where high throughput is necessary is when the sheer variety of parts is high. Instead of mass production, where part throughputs must be high, but part programming is usually fairly simple, or precision manufacturing, where throughput is low, but the part programs are usually quite elaborate, there also exist users who must inspect literally thousands of different, usually simple, parts. The option of *any* part programming is usually quite literally out of the question.

Technical Arts was commissioned by a major aircraft manufacturer to examine the feasibility of inspecting formed tubing. Tubing, bent to fit in the confined spaces of an airframe, is used to carry power, hydraulics, fuel, air, oxygen, and basically everything else that moves around an airplane. There are approximately 7,000 different tube designs used in any one airframe. The specifications are reasonably critical, the bending process imprecise, and the scrap rate high.

If TAC could devise a way to measure these tubes, especially if the bending process could be controlled in-line, then the value of such a machine would be tremendous. On the other hand, if the machine required so much as one man-day of part programming per tube, those programming costs would outweigh the benefits. TAC was asked if we felt we could down-load the part bend program, the instructions to the bender which makes the tube, and use *that* to program our machine. On top of that, they wanted no part fixturing (no special setup or configuring of the part and absolutely no tooling). They wanted to toss the part on a table, enter the part number (one of thousands), and press "go". Our first reaction was horror. This really *was* "A.I.".

After discussing this application with Tomas Lozano-Pérez and Eric Grimson of the M.I.T Artificial Intelligence Labs, we decided to proceeded on a study to see if a matching technique they developed called "RAF" could be utilized to provide the robustness and reliability of hand programming and hard fixturing without any operator intervention by utilizing the part model available in a CAD database. Their algorithm was capable of matching range data from a part to a polyhedral model description (as well as being able to work with 2-D and tactile data) [8, 9]. This could be used to generate a part program by utilizing it in the two principal steps needed:

1. **Path Planning** If a "sparse" data set of range data is acquired over the entire work volume (in this case 13' by 4' by 3') then this data can be matched to the part description, or model, to arrive at the location of the tube, the plan for acquiring detail measurement data, as well as other tasks such as collision avoidance analysis and occlusion (or shadowing) avoidance planning. In other words, the first pass figures out what we have for a part position, and what we can do in terms of taking measurements from it.
2. **Analysis.** The second pass is the "detail pass", so named because a small field of view scanner is used to acquire precise dimensional data from the tube. This scanner is guided over the tube based on the path plan from the first pass. In this pass, it is critical that any erroneous data be filtered out of the measurements prior to reporting the results back. The tube model can again be used to insure the analysis pass is not prone to occasional misallocation of data points.

The RAF method is quite simple: the range data is reduced to a set of simple "features" or hypotheses. In the case of the tube scanner, a cylinder, or leg, is a feature. These are taken pairwise and the relationship between the two legs, such as their relative angle, shortest distance, and lengths, is compared to similar relationships within pairs of legs in the model data set. This model data is precomputed, along with tolerance zones to allow rough matching when a parameter is not critical. When two pairs match particularly well, a trial match is made between all of the legs of the model and data sets. If essentially all of the data sets match well with the model, a full match is asserted.

The low level hypothesis algorithm [6] was specifically designed to make the RAF algorithm work on the cylindrical tube cross sections, unlike the original polyhedral models of the literature. This is still the least general purpose aspect of not only RAF, but most model-based higher level vision. The low-level algorithms are still surprisingly application specific.

On the other hand, the RAF algorithm itself worked remarkably well, and the tube scanner is today performing accurate inspections of tubing, as well as rapidly correcting bend programs at the aircraft plant, usually in one pass.

As an epilogue, however, we have a rather cautionary tale of automation run amok. Calibration is one of the earliest and most thoroughly examined algorithmic issues at TAC. We have designed some very simple calibrations, such as are found on our favorite 100A and 100X scanners. We also have designed some very exotic calibrations, such as are found on some of our more "advanced" systems. These are typified by calibration gauges which have dozens of facets, are meticulously machined and certified, and cost fabulous amounts of money. The software is designed to automatically acquire data from the gauge, segment it (although there's no RAF here), and regress, in effect, tens of thousands of measurements into a precise calibration matrix. When they work, they're a wonder to behold. They usually don't.

The fault isn't with our systems or the supremely skilled software engineers who devise the calibration algorithms. The fault is in the bundling of all calibration steps into a single black-box. Calibration is the process of measuring and correcting disparities between assumed and actual alignments and configurations of components. This is a very knowledge-intensive process. It requires a reasonably deep understanding of optics, thermodynamics, and, most of all, mechanics. It is invariably inappropriate to conceptualize calibration as the solution of the a pseudo-inverse of the calibration matrix. A pseudo-inverse doesn't know run-out from random noise.

We have recently redefined all of our calibration procedures to require substantially more operator involvement. The software, called CalMenu, is brutally simple. The procedures often involve dozens of steps, not one. Initial tests indicate that it will probably work for all our systems, big and small, and should actually take less time than the one-button wonders of the past. In any case, our systems usually don't need frequent calibration, so automating it simply doesn't make much sense.

Where Does This All Lead?

TAC will always work to improve the speed, reduce the cost and improve our accuracy specifications further. Some people don't consider 0.0002" accurate, although there are few systems of *any* kind with specifications much better than this on the factory floor.

The foregoing discussion clearly leaves us with the understanding that increasing the volume of data we can acquire requires us to address the issue of how to manage the data and reduce the load on the customer brought on by the added opportunities this improvement creates. The use of model information was one way of easing the load. Computer Aided Design (CAD) systems are a common source of such data.

On the other hand, surprisingly few CAD databases exist, and those that do are frequently unavailable or inappropriate for use in assisting part inspection.

TAC has, in fact, a product, the 200X, which is marketed specifically to digitize models for CAD input. These models may be "golden" parts which are used as prototypes, or were designed before CAD was available. They may be models for tools and dyes which wear and require frequent checking. They may be parts for which no drawings exist. Most commonly, the 200X is used by designers for such items as automobiles, and consumer electronics. The design process is iterative; design on CAD, fabricate the model, play with it, and redigitize on the 200X. The sophistication of our modeling software and the CAD packages is becoming quite impressive.

For other parts, however, there needs to be a way to generate models from scan data with the minimum of operator intervention. As before, fully automatic means are probably unrealistic and unwise approaches. What set of robust yet intelligent "tools" can we devise to greatly enhance a users capability to generate good part models rapidly, reliably, and with a minimum of intervention? This is the new challenge posed to companies like TAC, companies in the CAD business, as well as for the research community in machine intelligence as a whole.

Conclusion

We have seen how an attempt to solve a particular industrial measurement problem inadvertently turned into a machine vision company committed to addressing a broad range of measurement product issues. We suggest that this is not an unusual case, particularly in high-technology industries, and that carefully plotted strategies could not have provided TAC with those insights only the marketplace and time can provide. TAC, it would seem, had picked one of the "easier" fields of Machine Vision — Measurement, yet the lessons learned by our company in the marketplace over the eight years would have stunned the small group which started it. Indeed the marketplace, at once infatuated and naive in the early days with our industry, today has a level of maturity and sobriety which makes possible truly significant contributions by companies like TAC to productivity, quality and profitability. We are seeing systems incorporating the dreaded hydra "AI" actually reporting return on investment. Instead of merely Fortune 500 R&D labs buying systems for "factories of the future", we have small manufacturers buying systems so they can make next quarters production needs.

We've touched upon a few of the areas we think need more attention in the future, such as reliable segmentation methods in low-level vision both for model based and non-model based algorithms. The latter is of particular interest for model generation in CAD, a market area of significant importance to both the design and manufacturing communities and the companies that serve them.

A great deal remains to be done at TAC, and we've only touched on a couple of issues. We could have touched on many others such as cost, customer support, or any number of significant issues. What is important, however, is that a basic technology has been brought successfully to market with the support of capable researchers and substantial customer input. Although it hasn't ever been easy, its been a remarkably rewarding experience for both.

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