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Machine Vision-Based Alignment: Space to Factory to Garage

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Abstract

Machine vision is an enabling technology for many applications but “alignment” is arguably the most useful application class. Alignment is the task of “finding the position of a landmark or work piece in the electronic image” so that it can be tracked, moved, followed, or otherwise adjusted.

Many early alignment applications were in aerospace and defense. The visual ‘landmark’ they used was a star, a constellation or a laser-designated target. These applications made possible highly stable satellite platforms, accurate antenna aiming, and accurate military ordinance that are simply not possible with any other technology. These ‘aiming’ applications were extensions of traditional gunsighting techniques and nautical navigation.

In factory automation, vision-based alignment continues to play a key role in the semiconductor and electronics manufacturing revolution. Robotic machinery requires precision guidance to mate work pieces (dice and printed wiring boards) with process machinery (bonders, saws, and robots). Machine vision technology arrived just in time to make this possible, and new developments continue to improve precision and productivity in this area.

New alignment applications are emerging in unexpected areas, such as the automotive service garage. This paper describes a new automotive service application for vehicle wheel alignment. Two machine vision cameras measure the position and attitude of four wheel-mounted targets as the vehicle rolls and is steered. Six axes of rotation are used to define locations and orientations of the axles in three dimensional space. Their values are visibly inferred and measured, and their geometric relationships computed. The measurements are compared against the vehicle's ideal design tolerances for adjustment and repair purposes.

Keywords: machine vision, computer vision, alignment, vision applications, automotive

1. Introduction

Machine vision technology applied to industry is sometimes stereotyped as either inspection (accept / reject) or reading (OCR or Optical Character Recognition). For inspection, visible characteristics are collected to determine whether or not an article is acceptable or meets a set of quality-related criteria. For OCR, markings are read for identification purposes, such as a pharmaceutical lot code printed on a label. While these application areas are indeed valuable, they are dwarfed in industrial importance by alignment. Alignment is the task of “finding the

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position of a landmark or work piece in the electronic picture" so that it can be tracked, moved, adjusted, or otherwise processed.

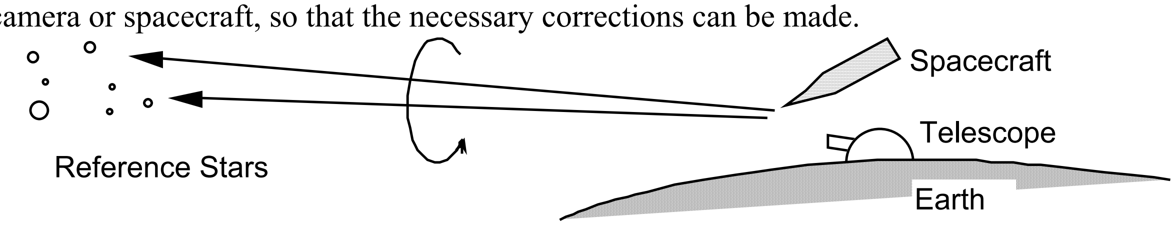
Alignment has made possible a much greater level of mass production, notably in microelectronics. Modern levels of industrial automation technology would not be possible without guidance provided by "robotic eyes" that find and position the work pieces. While it is true that "you can't inspect quality in" during manufacturing, it is possible to prealign constituent pieces before assembly to increase the quality of the operation. Alignment is inherently part of a closed loop process control, where the positional information is the feedback data. Inspection is usually outside or after the end of the process loop. Alignment in its broadest sense also includes automatic vehicle guidance and navigation, where the camera tracks the road to keep the wheels on course.

There is a great number of vision applications that involve alignment relative to a work piece or a landmark. The object of interest is found in the image and its location (image coordinates) are transformed into "real world" space so they can be used for machine control, such as an adjustment in position.

2. Space

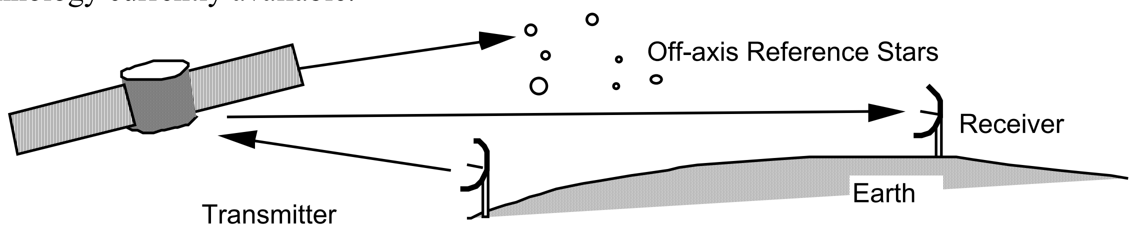
Some of the earliest applications for alignment were related to astronomy, for military and aerospace navigation and guidance. These are the direct descendants of nautical navigation techniques that have been refined over thousands of years. One of the basic principles is illustrated in the long-exposure image of the night sky below. The axis of rotation is visible as the center of the circular pattern. In this case, the motion is caused by the earth's rotation, and Polaris is at the center. The subtended angle that the stars have rotated indicates the photo's total exposure time as a fraction of a full one-day cycle.

By matching and comparing two images taken at different times, an image processing system can determine parameters like the rotational speed and the direction of the axis of rotation. From these measurements, the control system infers the motion of the sky relative to the camera or spacecraft, so that the necessary corrections can be made.



Communications satellites require that their antennae be aligned with earth stations. If the satellite drifts or wobbles, the antennae become misaligned, causing an interruption in the communications links. Early satellites stabilization systems used gyroscopic momentum wheels to keep the antennas aimed within about 0.5 degrees. This was adequate when the antenna beam was broad (several degrees). Satellites like the Nimbus earth observer used an "horizon scanning" technique to keep its instruments pointed toward a spot on the earth, while others referenced the sun. Unfortunately, both the earth and the sun undergo changes with time such as day/night cycles and solar flares. These changes make them less optically stable than distant stars, the ultimate landmarks.

The stability requirements of satellites have relentlessly increased. Modern satellites have narrow "spot light" beams that are only a fraction of a degree wide. These narrow beams require much greater pointing accuracy and stability in all three axes.   This requires very fine position control, of the type provided by referencing guide stars with machine vision technology. Accuracies measured in hundredths of a degree are now achieved, with substantial benefits in both performance and cost. This is the most accurate navigational technology currently available.

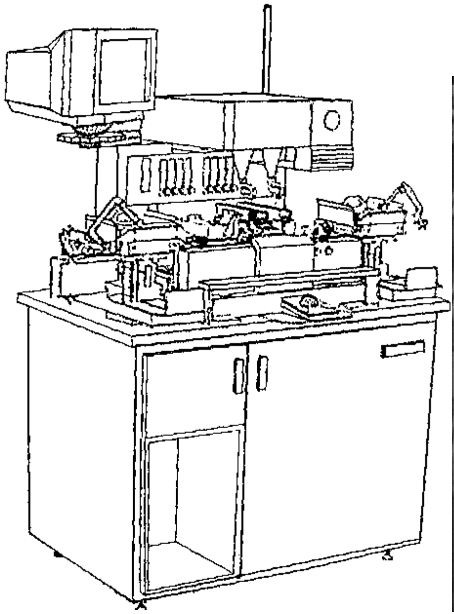


A more highly automated spacecraft is the Hubble Space Telescope, which selects its own guide stars based on a computerized "sky map" data base of star positions and brightnesses. Images of the sky are acquired through electronic camera and correlated or matched against a digitized map of the sky stored in a computer memory on board the craft. The map is a direct descendant of the Messier Catalog, first published in 1771, and contains bright stars, nebulae, and star clusters that are suitable for use as guide stars. The technique is highly accurate, both in terms of accuracy of constellation recognition and in angular precision.

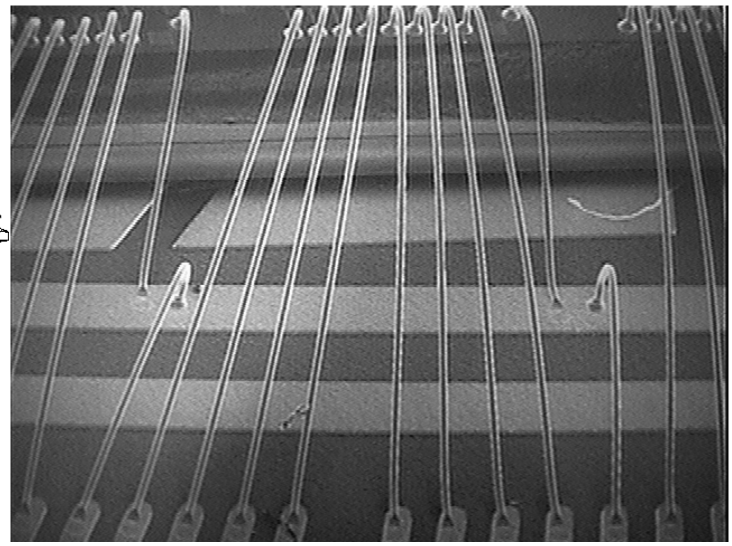
There are also many similar terrestrial applications of alignment. For example, the Multiple Mirror Telescope uses star images to keep its several optical mirrors aligned and stable. Military ordinance often uses 'artificial stars' as targets. For example, the Paveway guided bomb aligns itself towards a bright spot illuminated by a laser designator whose image is processed by on-board electronic system. "Heat seeking" missiles track the infrared emission image formed by hot engine exhaust. Work in all these applications has contributed significantly to alignment technology while achieving higher levels of performance than were previously unattainable.

3. Factory

Machine vision alignment continues to play a key role in factory automation for electronics manufacturing. One example is semiconductor wire bonding, where a silicon die is located on a lead frame to guide the robotic bonder machine. The operation is similar to a sewing machine. Automation would not be possible without precision visual guidance and is a key technology that has driven the "micro electronics revolution".



Abacus IIIsa Wire Bonder



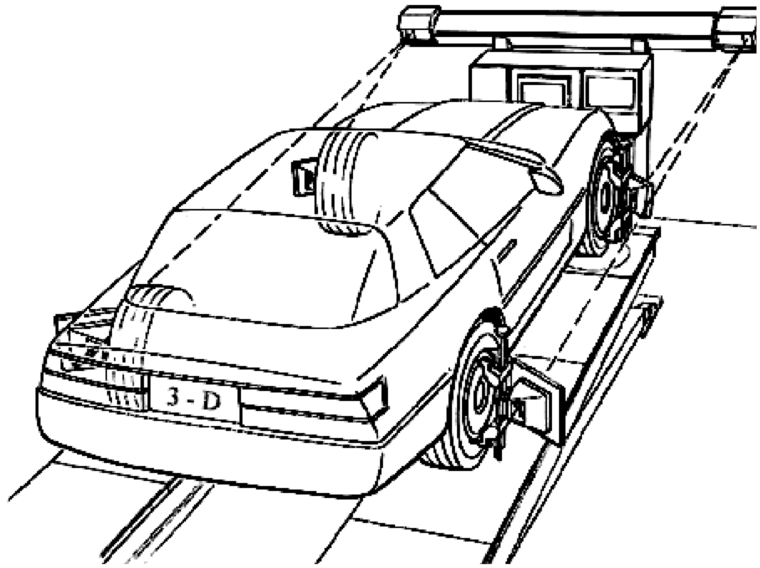
Bond wires attached to semiconductor die
(Illustrations courtesy of Texas Instruments, Inc.)

Bonder alignment was originally manually performed by operators looking through a microscope and making adjustments with a joystick. This provided accuracy is good at low speeds (one alignment every 3 seconds) but only for short periods of time. Modern automation machinery has improved this process to truly superhuman levels. Alignment accuracy is now 0.0002 inches, and runs at eight alignment cycles per second. This level of accuracy and speed is only possible with machine vision technology.

4. Garage

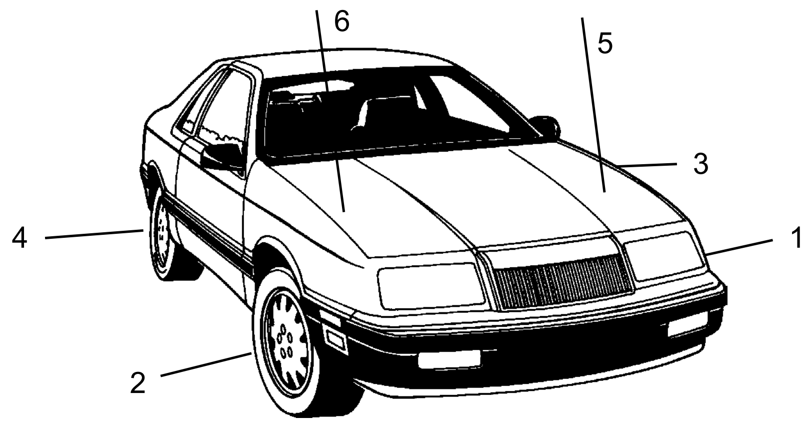
In 1997, the first vision-based automotive wheel alignment system was introduced, the "Visualiner 3D". It uses two cameras to observe the motion of four vehicle wheels, measure the six axes of rotation, and compare the readings against ideal specifications. The benefits that machine vision brings to this application are: faster operation, greatly improved accuracy and reliability, increased ruggedness, and reduced operating cost.

Periodic realignment of vehicle wheels is a common service that is provided by automotive service shops. The goal is to minimize road resistance under normal cruising conditions, and optimize handling for turns and emergency situations. The solutions to these problems are typically unique for different vehicles. This is caused by the profound differences in vehicle design objectives, and differences suspension designs are key.



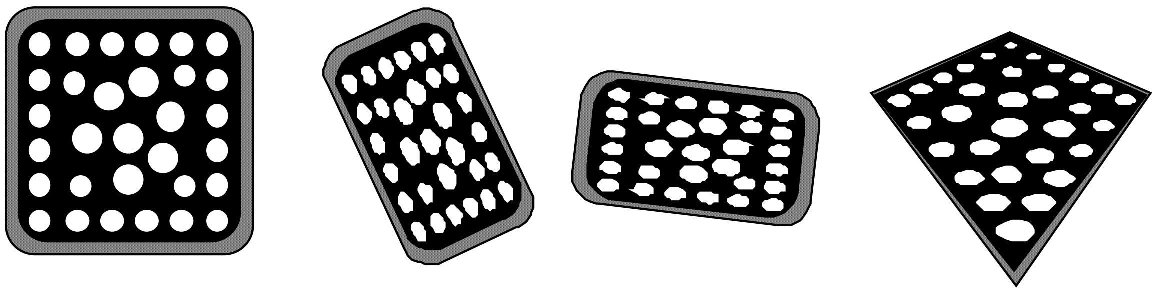
Wheel alignment involves the measurement of six invisible, theoretical lines about which the axes of the wheel move. In a conventional passenger car, these lines are:

- the rolling axes of each of the four wheels (1,2,3,4)
- the steering axes of the two front wheel suspensions (5,6)

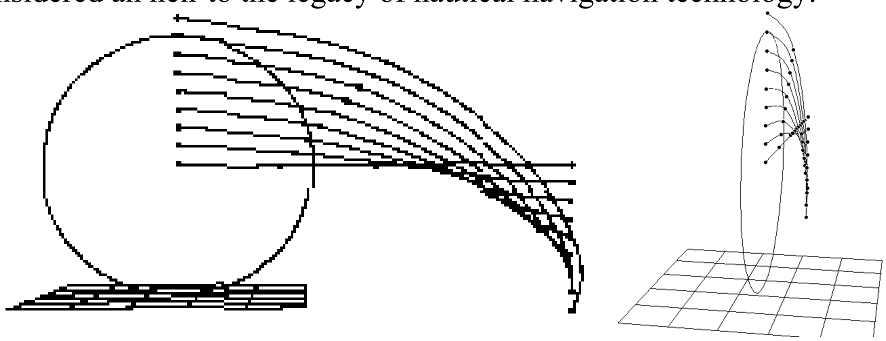


Each axis of rotation can be represented by line with position and direction in 3-dimensional space. The technician's objective is to make the rolling axis lines parallel under normal driving conditions (straight-ahead cruising at 55 MPH, two passengers, etc.) to minimize friction with the road (tire scrubbing). During turns, performance (handling) and safety are more important than friction. These simple objectives are difficult to achieve in practice, and suspension designers continue to develop better solutions with new vehicles. Typically, the manufacturer recommends a unique set of wheel alignment specifications and tolerances for each model vehicle. The specs are non-zero and are different for each vehicle. It is the task of the service shop to bring a battered suspension back to within the manufacturers' tolerances.

The 3D aligner's four targets are rigidly attached to the four wheels and move through space with the wheels. This makes the wheels visible to the cameras, which use them as uniquely identifiable fiducials or landmarks. As the target positions change, visible distortions are introduced from the point of view of the cameras and are measured by the vision system.



The wheel axes are measured indirectly by monitoring the position of each wheel as it moves through space, and then the 3-dimensional position of the axis of rotation is geometrically calculated. Since the fiducial target patterns bear some resemblance to star constellations, this could be considered an heir to the legacy of nautical navigation technology.



The targets traverse a predictable trajectory as the wheel targets roll through a cycloidal pattern. A time-lapse version is shown in the drawing above from two different perspectives. Because the targets and wheels are rigidly attached, their axes of rotation are coincident to each other and to the axle. Therefore the measurement of wheel axle position is not effected by random displacement of the specific points of attachment between target and wheel. These random displacements can be caused for example by dirt, human error, damaged vehicle wheels, or bent or worn target attachment assemblies.

Each target is prepared with a "constellation" of visible fiducial marks, and each mark is independently observed and measured by the cameras. Each mark's relative position within the constellation is matched against the idealized or 'golden' model in the data base. With each visible mark that is located in an image, the geometric accuracy of the match increases. With 36 marks on each target, a very high degree of accuracy is obtained with each image.

To measure the two steering axes for the front steered wheels (labeled axes 5 and 6 in the drawing above), a similar sensing and computational method is used. The vehicle is steered left and right, and the targets trace a cycloidal trajectory which is different from the rolling trajectory. The three-dimensional cycloidal functions define the two steering axes.

An unexpected benefit of machine vision in this application was the improvement in ruggedness of the equipment. Previous generations of alignment equipment relied on wheel-mounted "gravity gages" or electromechanical inclinometers that are subject to shock damage from drops. The Visualiner's cameras and electronics are all mounted away from the vehicle and out of harm's way. The passive targets have no active and no moving components, and can withstand considerably more abuse than electronic sensing equipment. In field use, a rule of thumb has emerged for the rugged vision targets: “if the target is not broken into pieces, then you can be confident that it is fully operational and well calibrated.”

In summary, machine-based alignment is continuing to be applied in new areas with considerable benefit in performance and operation. It has brought greater accuracy and faster operation to many industrial and aerospace applications, and we can expect more of the same in the future as steady improvements in this technology continue to emerge.

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