

Particle Tracking Applied to Flow Analysis

1. Specific Objectives

The objective of the proposed project is to make commercially available, an image analysis system to be used in the design of advanced devices used in fluid flow applications like biological organ implantation, chemical process equipment, aircraft and automobiles.

The image analysis system (TRACK) contains relevant commercially available hardware and software and will also contain custom designed software. It will provide the following functions:

- Synchronization of various devices in the apparatus
- Image Acquisition, compression and storage
- Image preprocessing (filtering, transformation)
- Particle image identification
- Particle path determination
- Validation and velocity map generation
- Data analysis (statistical and visualization)

The system will be extensively driven by parameters for easier adaptation to different flow configurations. It will feature an easy to use Graphical User Interface consistent with the current standards for the Microsoft Windows platform.

The existing prototype image analysis software developed by the investigators at the Pittsburgh Energy Technology Center has demonstrated the validity of the concept used in the particle path determination step for fixed frequency analysis.

The proposed project (during the project year) intends to

1. enhance the image analysis portion of the fixed frequency analysis
2. develop new algorithms for arbitrarily coded pulse analysis and implement/test them
3. implement the system on Microsoft Windows platform for 'off-the-shelf' use
4. add image acquisition, preprocessing capabilities and tools to visualize the resulting velocity maps

TRACK will be available for commercial use in 'shrink-wrapped' form at the end of the project. In the proposed year, development, packaging, and Beta installation of the system will take place. Some parallel effort at product introduction and exposure is necessary and will be done through conferences and exhibitions.

After the proposed year, focused marketing and product enhancements (e.g., to analyze particle flow in three dimensions with more than one camera image) will be the primary activity leading to a higher market share and niche in the technology area. Both these phases will require additional personnel employment at Effective Automation Systems Inc. This project will be the basis for establishing Effective Automation Systems as a strong player in world-wide high technology market, eventually leading to other product developments and corresponding growth.

2. Background

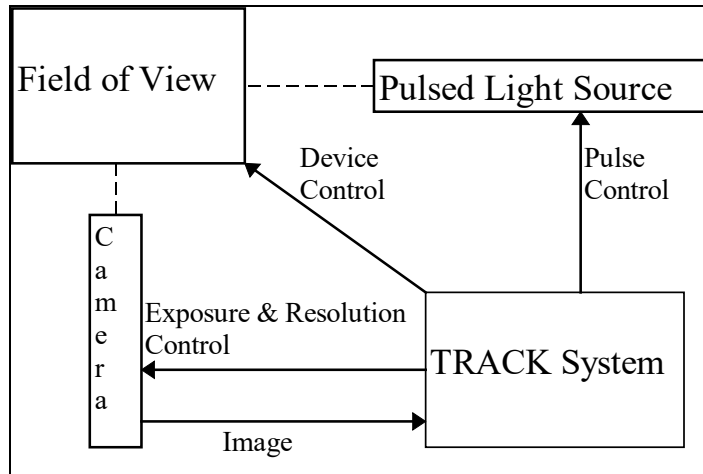


Figure 1

A schematic of the apparatus required for the Multiple Pulsed Particle Image Velocimetry (MPPIV) technique is shown in Fig 1. In the MPPIV technique used for flow velocity measurement, the fluid flow is seeded with fluorescent particles and the scene is illuminated with pulsed light source, typically a laser. The entire pulse train can be programmed from a computer and delivered via an integral pulse generator. The resulting digitized images are captured and automatically analyzed by the software in

order to obtain a velocity map of the fluid flow. The technology has been originally developed and prototyped in the Particle Flow Analysis Lab of the Pittsburgh Energy Technology Center and has been already successfully applied to a variety of flow configurations.

The pulse train controlling the light source defines the resulting image and hence the image analysis algorithm. Figure 2 depicts a commonly used fixed frequency, constant width pulse train with a definite number of pulses per exposure duration. The resulting particle images are correlated based upon the estimated maximum velocity, maximum acceleration in the flow field and the number of pulses delivered. Figure 3 illustrates one example of arbitrarily coded pulse train and the images resulting from it. Although the resulting image exhibits a higher degree of correlation between multiple images of a particle along its path and the direction of motion of the particle can also be determined, this technique is more vulnerable to problems of particle image fragmentation and is more computationally complex.

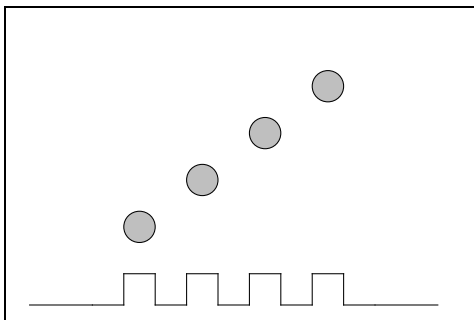


Figure 2

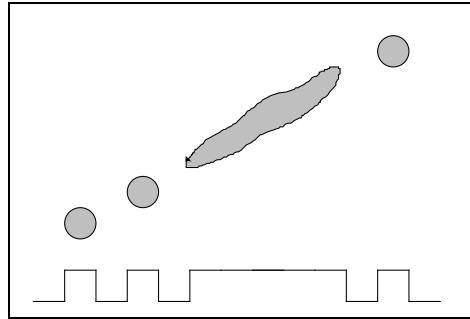


Figure 3

The MPPIV system at the Pittsburgh Energy Technology Center was developed initially to characterize fluid motion in coal combustion processes. A SPARC based computer with an image processing board capable of parallel processing is being used for image acquisition and analysis. Flow around a number of device designs have been studied using this facility via Cooperative Research and Development Agreement (CRADA) with University of Pittsburgh and other medical implantation device manufacturers. The investigators of the proposed project have designed and developed algorithms for image analysis currently being used in the facility.

The Novacor Left Ventricular Assist Device (LVAD) is an example of a device that was studied using this apparatus in an effort to analyze the flow pattern and locate regions of lower velocity; such reduced flow is well known to be associated with the development of thromboses. The fixed frequency analysis algorithm, which was at that time under development by the investigators, was used to obtain quantitative velocity data at various precise times during the one second cycle of the device.

3. Project Description

During the project year, TRACK system will be built and subjected to Beta testing at one or two specific sites. Based upon the resulting experience, enhancements to the existing features will be introduced in the market. After the proposed year, focused marketing will take place. This will lead to more product features (e.g., to analyze flow in three dimensions with more than one camera image) leading to a higher market share and niche in this technology area.

TRACK system will initially be capable of performing the functions listed as follows. A specific approach to the implementation of each step is also presented.

Synchronization

To achieve superior image quality, both the light source and the camera should be programmable and the control signals to both devices should be synchronized. Such a synchronization minimizes the residual image effect. Residual image effect is due to the slow decay (compared to the exposure time) of fluorescent images resulting in erroneous particle images.

In the study of periodic pulsed devices (e.g., flow through artificial heart valves), there is an additional need to determine the flow at precise times during the cycle. The system shall be capable of delivering control pulses to the process device and be capable of synchronizing this pulse with the above two control signals.

The user will be able to input the above three pulse trains and define the relative offsets of each. TRACK will interface with one specific third party pulse generator board and software drivers to implement this function.

Image acquisition, preprocessing, compression and storage

There is an abundance of products on the Microsoft Windows platform to accomplish these standard imaging functions. Utilizing the Dynamic Data Exchange and Dynamic Link Libraries features of Windows, TRACK will interface with an existing software that supports these features and also has extensive programmability. The macro language available with this software package allows TRACK to customize the user interface, while utilizing the image processing capabilities provided with the package. Such an integration will result in a consistent user interface and support to a variety of acquisition devices.

Particle image identification and feature extraction

This step is dependent on the input pulse pattern. Specifically, short duration pulses produce a 'dot' and long duration pulses produce a 'streak'. Isolating the noise and fragmented particle images from the useful data is a complex task and is based upon rules defining the anticipated features of the particle.

The particle coordinates and its characteristics constitute the results of this step.

Particle path determination

The particle images resulting from individual pulses need to be correlated to derive the particle path.

For **fixed frequency constant width pulse** technique, the prototype software has been designed to be flexible, tolerant of potential errors in earlier steps and highly configurable for individual flow scenarios. The algorithm forms search trees constituting the candidate particle images along a path as described below.

Starting from a candidate primary initiator image, based upon the maximum anticipated velocity (supplied as a parameter) a list of candidate secondary initiators is formed. For each pair of initiators, the expected location of the next particle image can be obtained either from a flow field model (which the user can provide as a 'module') or based upon linear extrapolation. From this extrapolated location, and based upon the maximum anticipated acceleration, or a tolerance (supplied as a parameter), a list of candidate particle images can be found. The extrapolation is repeated with the newly obtained list, and process continues ultimately resulting in a search tree with arbitrary number of nodes at each level. The algorithm can also be configured by the user to tolerate a specified number of 'missing' particle images that may be due to poor image quality or errors in the image preprocessing. These missing particle images need to be subsequently be validated by the presence of real particle images in order to be part of a particle path.

Based upon rules (e.g., estimated curvature of particle paths), one path along this search tree is chosen as the real particle path. In flow configurations with a large variations in velocity or accelerations, the entire method can be repeated on the same frame first with smaller values of maximum velocity and/or acceleration and progressively increasing settings to improve the reliability of the algorithm.

In the **coded pulse analysis**, typically one wide pulse is used in the pulse train resulting in a 'streak' type particle image. The analysis algorithm should extract the length and direction of the 'streak'. The

information derived from the streak substitutes the initiator pair discussed in the previous fixed frequency analysis method. If asymmetric number of smaller width pulses are used on either side, the direction information can also be obtained.

The fixed frequency constant width analysis technique has been prototyped and tested at the Pittsburgh Energy Technology Center. Design changes to make this algorithm more parameter driven, add trace and debug options and implement a Windows user interface are needed. The coded pulse analysis needs to be designed and built, using the data structures already existing in the fixed frequency constant width analysis.

Velocity map generation

Manual validation of the particle paths may be necessary in certain flow situations either due to a high particle concentration leading to erroneous paths or due to high variation in velocity or acceleration in the flow field that could not be handled even with repeated parameter settings.

Once the particle paths have been determined, the user will have the option to

- view the results on an individual frame basis, or collective basis
- manually include/exclude individual particle paths from the output
- automatically generate velocity data for all paths

The output data will also be generated in formats consistent with popular database and/or spreadsheet programs.

Data analysis

Data analysis involves statistical averaging, interpolation, graphs, vector and contour plots all of which are available in a variety of software packages for the PC market. TRACK will use the Dynamic Data Exchange and Dynamic Link Libraries features of Windows to integrate with one specific package. In addition, the user will have the option to choose a file format consistent with popular database and/or spreadsheet programs.

4. Stage of R&D

Part of the project is based upon an prototype which has demonstrated the proof of concept using some sample applications. The proposed development and commercialization project will use the experience gained in the previous work to improve the system capability and to develop newer techniques. During the same period, Beta testing and initial preparations for commercialization will take place.

5. Commercialization

- 5.1** The project proposes to introduce an image analysis system for commercial use at the end of successful project completion. The features of the system and the definite approach to be followed in the design are discussed in detail in sections 1,2 and 3 above.
- 5.2** The need to measure flow velocities in highly turbulent flow systems exists in (i) artificial organ implantation design and approval process (ii) design of aircraft and automobiles (iii) design of

chemical process equipment (reactors/heat exchangers) desiring to produce high levels of mixing of process streams. Specific customers in each of the above market segments have expressed interest in the proposed system. The prototype software was featured during an expo at a recent course on *Application of Particle Image Velocimetry* on March 14-18 at DLR, Gottingen Germany and has evoked interest.

Current world wide market need is estimated at about 500-1000 installations. In addition to the market segments mentioned above, in which specific customers are known, it is expected based upon published literature, that the need to track particle paths exist in particle physics and nuclear research areas. With rapid advances in imaging and optical equipment, the market is estimated to grow to 2000 installations in next three years. Each system is expected to be priced about 25000 - 100,000 with varying degrees of capabilities and system support.

5.3 The commercially available software package 'Visiflow' from AEA Technology in Europe is a potential competitor. They have the advantage of having a commercial product and association with a laser manufacturing company. However, the particle tracking algorithm component of it is lacking both in depth and flexibility; instead the authors concentrate on details of image acquisition and velocity map visualization. TRACK will focus on its superior, customizable particle tracking algorithm and associated user interface. The image pre-processing and data analysis functions will be achieved through integration with existing and popular third party software, thus achieving a higher degree of combined quality. Existing track record of the prototype system in use at the Pittsburgh Energy Technology Center will help in marketing to other research institutions and forming marketing alliances with laser manufacturing systems.

5.4 The market for the product is highly specialized as indicated in 5.2 above. Several focused strategies will be used to reach the customers. They include

- Publications and presentations in specific select conferences
- Participation in product expositions
- Partnership/alliances with optical equipment manufacturers

As described in Section 3 above, TRACK system involves software written to address specific functions required by the system. The remainder of the functionality is achieved through integration with existing software packages. This results in

- focused future development and improvement in the area of specialization of the company
- faster response times to provide upgrades for evolving imaging hardware and visualization software

At the end of the project period, it is anticipated that the company will be positioned strategically to capture about 5% of the market share that will increase to about 25% in five years.

5.5 Mr. Srinivasan, the President of Effective Automation Systems, Inc., will serve initially as the project director and at the end of the project period, define the key directions for the product and the company.

Mr. Ramgopal, will serve initially as the Systems Designer and Integrator responsible for the acquisition and integration of various pieces of equipment. At the end of the project period, he will serve as the key development manager.

It is anticipated that a computer science graduate student may be needed during the project phase to participate in the design and implementation of algorithms. This would be the only anticipated employment during the project year.

At the end of the project year, at least one full time analyst and sales person and other administrative support staff will be needed to support existing installations and handle new customers. This will result in a total of four to five employees for the second year. The third year expansion, if any, will depend on the performance during the previous years and has the potential to reach about 20.

5.6 N/A

6. Facilities

The system development and prototyping will take place at the premises of Effective Automation Systems Inc. The MPPIV technique requires capital equipment which is typically only available at corporate and institutional Research & Development facilities. Arrangements with University of Pittsburgh and/or Pittsburgh Energy Technology Center will be established using the existing working relationship between the investigators with both institutions.

7. Project Evaluation

The developed TRACK system will be evaluated and tested by applying it to representative images already available due to the previous work mentioned in Section 2. Additionally, the system will be provided for use at selected Beta sites. This effort has several definite goals:

- To establish the feasibility of a configurable commercial system applied to a generic flow scene
- To evaluate the performance of the commercial product w.r.t. analysis methods already available
- To obtain feedback from the users regarding the parameters and graphical interface
- To identify areas of future work

8. Key Personnel

The principal investigator and the project director for the proposed project, Mr. Srinivasan, has a Master of Science degree in Chemical Engineering specializing in fluid mechanics and has an extensive experience in real time and instrumentation systems and software. He was the lead technical engineer in the design and development of algorithms for image analysis of MPPIV system operational at the Pittsburgh Energy Technology Center. He collaborated with the Principal Investigator of the Particle Flow Analysis Facility in assisting University of Pittsburgh and several other implantation device manufacturers study the flow field around their respective devices. Currently, Effective Automation Systems Inc., fully owned by Mr. Srinivasan has a contract to provide image analysis support for the various ongoing experiments at the facility.

Mr. Bala Kumar, who will serve as a consultant in this project, has a Master of Science degree in Mechanical Engineering and has an extensive background in machine vision and image processing. During his more than eight year tenure at the Robotics Institute at Carnegie Mellon University, he has worked on several high technology imaging projects. He also served as a consultant to Baxter Novacor and collaborated in the design of algorithms for image processing of the Left Ventricular Assist Device flow analysis.

Mr. Ramgopal who will serve as a systems designer and integrator has a Master of Science degree in Computer Science and has extensive experience in real time systems software and project management. His vast technical and managerial experience will also contribute to the successful commercialization of the product.

The detailed profiles of the above three investigators is enclosed.