Task 22

Design Concepts and Process Analysis for Transmuter Fuel Manufacturing

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BACKGROUND

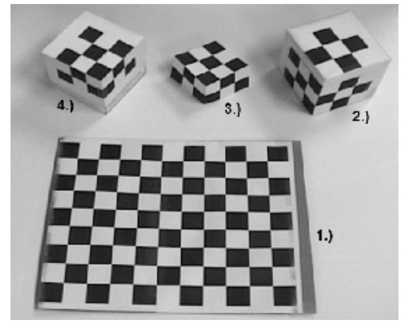
The safe and effective manufacturing of actinide-bearing fuels for any transmutation strategy requires that the entire manufacturing process be contained within a shielded hot cell environment. To ensure that the fabrication process is feasible, the entire process must be designed for remote operation. The equipment must be reliable enough to perform over several decades, and also easy to maintain or repair remotely. The facility must also be designed to facilitate its own decontamination and decommissioning. In addition to these design factors, the potential viability of any fuel fabrication process will also be impacted by a number of variables, such as the current state of technology, potential problem areas, deployment scaling, facility safety, and cost.

RESEARCH OBJECTIVES AND METHODS

The goal of this research project is to provide technical support to process designers working on the development of the fuel cycles for transmutation applications. Detailed process models have been developed to better define the impact of fuel choice on the transmuter fuel cycle, including relative process losses, waste generation, and plant capital cost. These process models provide insight regarding required plant size and number of plants needed to mesh with the fuel recycling line. They also determine requirements for automation.

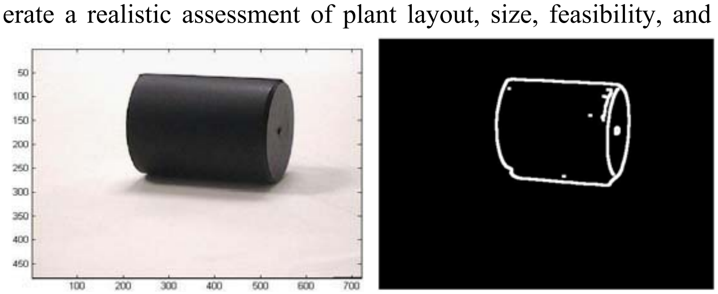
Manufacturing models for large-scale production in a hot cell environment have also been developed. Combined, these two models allow the assessment of plant layout, and provide the framework for estimation of plant capital and operating cost estimates, and for feasibility in general. The operations of robotic equipment and the sensor technology required for safe ad reliable robot control have been evaluated through simulations in three-dimensional space. The manufacturing technology developed for hot cell applications is also applicable to other, more general uses, where occupational hazards prevent human presence near processes.

The research work performed during the reporting period was divided into several tasks:



Calibration Objects

Simulations: This task modeled manufacturing processes to generate a realistic assessment of plant layout, size, feasibility, and technology development required for large-scale remote fabrication of fuel. Modeling of the candidate fuel manufacturing processes was performed using the MSC.visualNastran and ProEngineer simulation software tools. To date, the modeling of dispersion and tri-isotropic (TRISO) fuels for gas-cooled reactors has been completed. A parametric study to determine the process reliability and possible reliability improvements for various fuel types and equipment configurations is in progress.


CCD image (left), and Contour (right) of a cylinder

Cost, Feasibility, and Large Scale Deployment: This task will develop the database necessary to provide cost estimates and differential cost for various fuel manufacturing options. Cost estimates regarding projected capital cost, reliability, and plant life have been developed and are being refined as additional knowledge is developed.

Automated Vision-Based Image Acquisition and Robot Control: This task explores and demonstrates strategies for the reliable and flexible control of the material handling robots inside the hot cell by means of automated vision systems. Since the cameras can be positioned outside the hot cell, such systems would have significant advantages over sensors inside the hot cell, resulting in potentially reduced system maintenance and increased system reliability.

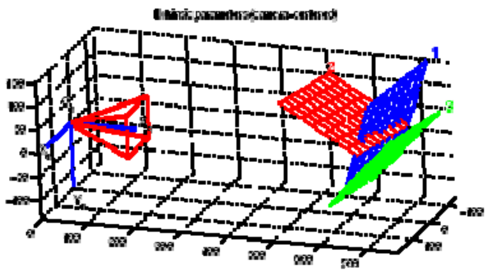
RESEARCH ACCOMPLISHMENTS

Research during the past year focused on vision-based recognition and spatial location of fuel pellets inside a hot cell.

Recognition of Cylindrical Fuel Pellets by the Charge-Coupled Device (CCD) Camera: The images of cylinders that are captured by the camera have properties which make the recognition of the cylinder more difficult. The real time cylinder pictures contain shadows as well as reflections (specularity) caused by lighting conditions. This project seeks to detect the cylinders' contours in order to identify and classify it correctly. Changes of lighting conditions can make the correct identification difficult at times.

Camera Calibration and Dimensional Measurements using the CCD Camera

Calibration objects: Calibrating a camera requires several corre-



Estimated 3D Structure of a calibration plane

sponding 3D and 2D points. Calibration objects are mostly planes or cubes (two or three orthogonal planes) with special markings. Here, those markings are chess board patterns with equidistant corners distributed accurately over the object surface. The corners define the known points in the world coordinate system and can be easily identified in the image from edge detection algorithms. This step provides the opportunity to estimate the projection matrix. Another method of calibrating is self-calibration. This technique obtains correspondences from the camera movement in a static scene using image information alone.

Estimation of the projection matrix: The camera calibration algorithm was programmed in Matlab. The regions of interest were defined for every single image by selecting the 4 outmost corners of the chess pattern. The Matlab software identifies and saves the positions of the individual black square's corners for processing. The optimization method of Levenberg-Marquardt is applied which also includes the adaptive correction of the lens distortion.

Two-View Triangulation: Triangulation is the process of finding the position of a point in space given its position in a stereo image pair. This task is essential for vision-based robot pick and place operations. The Linear-Eigenmethod is the simple triangulation method that is used for extracting the 3D points.

Optimal Triangulation: Suppose there are two point correspondences x and x' from two images, and the goal is to reconstruct the 3D point X. If the correspondences are accurate (which cannot usually be expected) the rays of x and x' will lie in the same plane and thus will intersect in X. In the presence of noise, accurate point coordinates cannot be expected. It follows that x and x' may not lie in a plane, which means that there is no intersection. A method for correcting the existing point correspondences such that the corresponding rays will lie in the same plane consists in finding a global minimum of a cost function. For this approach, it is assumed that the fundamental matrix is well defined.

Recognizing calibration cubes: Until now a disadvantage of the calibration process has been the need to determine the point correspondences of the calibration object and a given 3D model manually. A desirable feature would be the automatic mapping from calibration cube points to the 3D locations of a 3 plane model. This would allow estimating the projective matrix automatically. For the experimental validation, several calibration objects were arranged on a paper grid in order to cover multiple points in the 3D space.

ACADEMIC YEAR HIGHLIGHTS

- G.F. Mauer, "Equipment Redundancy and Plant Reliability in Robotic Hot Cells for Fuel Fabrication," *Proceedings*, American Nuclear Society Winter Annual Meeting, November 2006.

For the tests, 50 points were used to estimate the fundamental matrix. The same points have been reapplied as control points. The triangulation error was around 0.2 inches at a distance to the calibration points of 10 inches. In the proximity of the calibration points the error was below 0.1 inch. The errors are attributed by the following effects:

- Quality deficiencies of the camera device
- Inaccurate calibration objects (perpendicularity)
- Linearity of the algorithm

FUTURE WORK

Vision-based control of hot cell robots: Images of scenes inside a hot cell, such as fuel pellets, will be acquired in real time under varying lighting conditions and in increasingly complex environments. The development of algorithms for reliable object identification, for validation and measurement of the object geometry, location, and orientation, and for camera calibration, will continue.
Vision-based robot servoing: Using a Fanuc M-16iB industrial robot, the stereo vision system will be installed in lab Thomas Beam Engineering Building (TBE) Room B-162, and the task will proceed to test the visual servoing algorithms under more realistic conditions.

Tests of the camera system in noisy environments will continue for the vision system's ability to discern fuel pellets from other objects present.

The conceptual design plant layout, and cost estimates for possible Transmuter Fuel fabrication plants will continue for various fuel types. (Simulations of oxide, metallic, and dispersion fuels have been completed.)

Capital and operations cost estimates will be developed for various fuel options. Target Plant capacity approximately 100 metric tons annually.

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