NOTE TO USERS

The original manuscript received by UMI contains pages with indistinct print. Pages were microfilmed as received.

This reproduction is the best copy available

UMI
Implementation of Machine Vision Feedback into a Structurally Flexible Manipulator Testbed

by

Andrew C. M. Allen

A thesis submitted in partial fulfillment of the requirements for the Degree of Master of Applied Science, at the Institute for Aerospace Studies, University of Toronto

©1996 Andrew C. M. Allen
The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L’auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

L’auteur conserve la propriété du droit d’auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

0-612-29361-0
Abstract

Dynamic position feedback based on machine vision has been incorporated into a flexible manipulator testbed for the purpose of developing and testing vision-assisted servoing and visual servoing techniques. In particular, the Advanced Space Vision System (ASVS) has been integrated into the Radius facility at the University of Toronto. ASVS is a real-time photogrammetry system developed by the Canadian Space Agency and Radius is a planar manipulator testbed with structural frequencies similar to those of a real space-based manipulator such as Canadarm. Modifications to both the flexible manipulator and the vision system were required to allow ASVS to supply serviceable position data to the Radius control computer. Following the integration of the vision system into the servo loop, a complete characterization of the photogrammetric system as installed established the parameters under which control algorithms will operate. Emphasis was placed on determining the response time of the vision system and on comparing the anticipated experimental Radius behavior with the results of previous photogrammetric studies completed on-orbit.
Acknowledgments

I would like to thank Dr. Gabriele D'Eleuterio of the Space Robotics Group at the University of Toronto Institute for Aerospace Studies (UTIAS) and Dr. Steven MacLean of the Canadian Astronaut Program (CAP) for supervising this research programme.

I would also like to thank all the members of the Spacecraft Dynamics and Robotics Group for encouraging an atmosphere conducive to experimental successes. In particular, Thierry Cherpillod and Manfred Sever with deserve special recognition for their advice with hardware and software respectively. Samir Fahs of the UTIAS Hypersonics Laboratory provided valuable assistance with the communications software.

Dr. Mahlon Charlesworth, Raymond Kulchyski, Charles Perratt, and Dr. Lloyd Pinkney of the Institute for Aerospace Research (IAR) of the National Research Council of Canada (NRCC) played key roles in this study by preparing and releasing the Canadarm flight data. Many years of preparation and hard work were involved in producing a system suitable for space-based photogrammetry; IAR deserves congratulations on their achievements.

Paul Nephin, Dr. Michael Sink and John Schneider of Neptec Design Group Limited provided invaluable assistance with the ASVS laboratory prototype.

This research would not have been possible without the help of grants from Neptec Design Group Limited, the Canadian Space Agency (CSA) and the National Sciences and Engineering Research Council (NSERC).
Contents

1 Introduction .............................. 1

2 Background ................................ 5

3 Project Definition .......................... 10
   3.1 Flight Data Analysis ..................... 10
   3.2 Laboratory Implementation ................. 12
   3.3 Characterization .......................... 13

4 Flight Data Analyses ....................... 14
   4.1 Flight Data Handling ...................... 16
      4.1.1 Raw Data ............................ 16
   4.2 Linear Analysis ......................... 19
      4.2.1 Purpose ............................. 19
      4.2.2 Scope ............................... 20
      4.2.3 Data Handling ....................... 20
      4.2.4 Flight Data Analyses ................. 26
      4.2.5 Concluding Remarks - Linear Analysis 30
   4.3 Nonlinear Analysis ...................... 32
      4.3.1 Purpose ............................. 32
      4.3.2 Scope ............................... 33
4.3.3 Multiple Windowing ........................................ 33
4.3.4 Hilbert Space Analyses ................................... 35
4.3.5 Concluding Remarks - Nonlinear Analysis ......... 36
4.4 Comparison with Ground Testbed ....................... 38
4.5 Follow-up Experimentation ................................ 40

5 Physical Testbed ................................................. 44
  5.1 Manipulator System ......................................... 44
  5.1.1 Flexible Manipulator .................................... 44
  5.1.2 Target Manipulator ...................................... 46
  5.2 Photogrammetric Machine Vision Platform .......... 46
  5.3 Camera Positioning ......................................... 48
  5.4 Camera Selection ........................................... 49
  5.5 Target Array Design ....................................... 52
     5.5.1 Centroid Determination .............................. 52
     5.5.2 Planar Manipulator Target Final Design ......... 58
  5.6 Lighting .................................................... 59
     5.6.1 Wattage ................................................ 60
     5.6.2 Thermal ............................................... 60
  5.7 Connectivity ................................................ 60
  5.8 Measurement Transformations ............................ 62

6 Characterization ................................................ 66
  6.1 Camera Lens Calibrations ................................. 66
  6.2 Measurement Latency ....................................... 67
     6.2.1 Transducer Latency ................................ 69
     6.2.2 Communication Delay ................................. 69
  6.3 Sampling Rate ............................................... 70
  6.4 Precision .................................................... 71
List of Figures

2.1 The *Radius* Experimental Facility. .......................... 7

3.1 Arm Configurations for STS-52 Dynamics Experiments (SVS-9). 11

4.1 Sample Three-dimensional Vibrations for an SRMS Maneuver (transformed graphics filtering). .......................... 16

4.2 SRMS Joint Encoder Position Data vs SVS Position Data. . 17

4.3 Functional Block Diagram: Handling of SRMS Joint Encoder Data Downlink. .......................... 18

4.4 Pitch Plane and phase between OBAS X and OBAS Z Oscillations .......................... 21

4.5 Pitch Plane and phase between OBAS Y and OBAS Z Oscillations .......................... 22

4.6 Bode Plot of 12th Order Butterworth Low-pass Filter. .... 23

4.7 Linear Least-Squares Fit to a Typical Logarithmic Decrement Plot .......................... 26

4.8 SVS-9 Maneuver 1-1 (3 Axes) with Roll 19.48 and Yaw 8.4 . 29

4.9 SVS-9 Maneuver 1-1 (X Axis) with Roll 19.48 and Yaw 8.4 . 30

4.10 Logarithmic Decrement Plot - SVS-9 Maneuver 1-1 (X Axis) . 31

4.11 SVS-9 Maneuver 1-1 Power Spectral Density (X Axis) .... 32

4.12 Apparent Transition in Vibration Regime ..................... 33

4.13 Multiple Windowing of Vibration Data ....................... 34

4.14 Spiral Formed from Hilbert Transformation ................ 36
B.5 SVS-9 Maneuver 1-2 (3 Axes) with Roll 19.48 and Yaw 0 ...
B.6 SVS-9 Maneuver 1-2 (X Axis) with Roll 19.48 and Yaw 0 ...
B.7 Logarithmic Decrement Plot - SVS-9 Maneuver 1-2 (X Axis) ...
B.8 SVS-9 Maneuver 1-2 Power Spectral Density (X Axis) ......
B.9 SVS-9 Maneuver 1-3 (3 Axes) with Roll 19.48 and Yaw 0 ...
B.10 SVS-9 Maneuver 1-3 (Y Axis) with Roll 19.48 and Yaw 0 ...
B.11 Logarithmic Decrement Plot - SVS-9 Maneuver 1-3 (Y Axis) ...
B.12 SVS-9 Maneuver 1-3 (Z Axis) with Roll 19.48 and Yaw 0 ...
B.13 Logarithmic Decrement Plot - SVS-9 Maneuver 1-3 (Z Axis) ...
B.14 SVS-9 Maneuver 1-3 Power Spectral Density (Y Axis) .......
B.15 SVS-9 Maneuver 1-3 Power Spectral Density (Z Axis) .......
B.16 SVS-9 Maneuver 1-4 (3 Axes) with Roll 19.48 and Yaw 0 ...
B.17 SVS-9 Maneuver 1-4 (Y Axis) with Roll 19.48 and Yaw 0 ...
B.18 Logarithmic Decrement Plot - SVS-9 Maneuver 1-4 (Y Axis) ...
B.19 SVS-9 Maneuver 1-4 (Z Axis) with Roll 19.48 and Yaw 0 ...
B.20 Logarithmic Decrement Plot - SVS-9 Maneuver 1-4 (Z Axis) ...
B.21 SVS-9 Maneuver 1-4 Power Spectral Density (Y Axis) .......
B.22 SVS-9 Maneuver 1-4 Power Spectral Density (Z Axis) .......
B.23 SVS-9 Maneuver 2-1 (3 Axes) with Roll 19.48 and Yaw 8.3 ...
B.24 SVS-9 Maneuver 2-1 (X Axis) with Roll 19.48 and Yaw 8.3 ...
B.25 Logarithmic Decrement Plot - SVS-9 Maneuver 2-1 (X Axis) ...
B.26 SVS-9 Maneuver 2-1 Power Spectral Density (X Axis) .......
B.27 SVS-9 Maneuver 2-2 (3 Axes) with Roll 19.48 and Yaw 0 ...
B.28 SVS-9 Maneuver 2-2 (X Axis) with Roll 19.48 and Yaw 0 ...
B.29 Logarithmic Decrement Plot - SVS-9 Maneuver 2-2 (X Axis) ...
B.30 SVS-9 Maneuver 2-2 Power Spectral Density (X Axis) .......
B.31 SVS-9 Maneuver 2-3 (3 Axes) with Roll 19.48 and Yaw 0.5 ...
B.32 SVS-9 Maneuver 2-4 (3 Axes) with Roll 19.48 and Yaw -1.875
B.33 SVS-9 Maneuver 2-4 (Y Axis) with Roll 19.48 and Yaw -1.875 108
B.34 Logarithmic Decrement Plot - SVS-9 Maneuver 2-4 (Y Axis) . 108
B.35 SVS-9 Maneuver 2-4 (Z Axis) with Roll 19.48 and Yaw -1.875 109
B.36 Logarithmic Decrement Plot - SVS-9 Maneuver 2-4 (Z Axis) . 109
B.37 SVS-9 Maneuver 2-4 Power Spectral Density (Y Axis) . . . . . . . 110
B.38 SVS-9 Maneuver 2-4 Power Spectral Density (Z Axis) . . . . . . . 110
B.39 SVS-9 Maneuver 3-1 (3 Axes) with Roll 19.48 and Yaw 6.597 . 112
B.40 SVS-9 Maneuver 3-1 (X Axis) with Roll 19.48 and Yaw 6.597 . 113
B.41 Logarithmic Decrement Plot - SVS-9 Maneuver 3-1 (X Axis) . 113
B.42 SVS-9 Maneuver 3-1 Power Spectral Density (X Axis) . . . . . . . 114
B.43 SVS-9 Maneuver 3-2 (3 Axes) with Roll 19.48 and Yaw 0.555 . 115
B.44 SVS-9 Maneuver 3-2 (X Axis) with Roll 19.48 and Yaw 0.555 . 116
B.45 Logarithmic Decrement Plot - SVS-9 Maneuver 3-2 (X Axis) . 116
B.46 SVS-9 Maneuver 3-2 Power Spectral Density (X Axis) . . . . . . . 117
B.47 SVS-9 Maneuver 3-3 (3 Axes) with Roll 19.48 and Yaw 0.555 . 118
B.48 SVS-9 Maneuver 3-3 (Y Axis) with Roll 19.48 and Yaw 0.555 . 119
B.49 Logarithmic Decrement Plot - SVS-9 Maneuver 3-3 (Y Axis) . 119
B.50 SVS-9 Maneuver 3-3 (Z Axis) with Roll 19.48 and Yaw 0.555 . 120
B.51 Logarithmic Decrement Plot - SVS-9 Maneuver 3-3 (Z Axis) . 120
B.52 SVS-9 Maneuver 3-3 Power Spectral Density (Y Axis) . . . . . . . 121
B.53 SVS-9 Maneuver 3-3 Power Spectral Density (Z Axis) . . . . . . . 121
B.54 SVS-9 Maneuver 3-4 (3 Axes) with Roll 19.48 and Yaw 0.555 . 123
B.55 SVS-9 Maneuver 3-4 (Y Axis) with Roll 19.48 and Yaw 0.555 . 124
B.56 Logarithmic Decrement Plot - SVS-9 Maneuver 3-4 (Y Axis) . 124
B.57 SVS-9 Maneuver 3-4 (Z Axis) with Roll 19.48 and Yaw 0.555 . 125
B.58 Logarithmic Decrement Plot - SVS-9 Maneuver 3-4 (Z Axis) . 125
B.59 SVS-9 Maneuver 3-4 Power Spectral Density (Y Axis) . . . . . . . 126
B.60 SVS-9 Maneuver 3-4 Power Spectral Density (Z Axis) . . . . . . . 126
C.1  Latency (ASVS only) Test Data Probability Distribution. . . . 129
C.2  Precision Test Data Probability Distribution. . . . . . . . . 130
List of Tables

4.1 Fundamental Natural Frequencies and Viscous Equivalent Damping Decrements for SRMS Reference Position #1 (Maneuver 1) ................................................................. 28
4.2 Fundamental Natural Frequencies and Viscous Equivalent Damping Decrements for SRMS Reference Position #1 (Maneuver 1) determined via Hilbert Transformation .............. 31
4.3 Fundamental Natural Frequencies and Viscous Equivalent Damping Decrements for Radius Comparative Test .......................... 39

6.1 Transducer (ASVS) Latency (in milliseconds) .................. 69
6.2 Transducer and Communications Latency (in milliseconds) .. 70
6.3 Vision System Sampling Rate Measurement (in milliseconds) . 70
6.4 Repeatability of Vision System Position Measurements (in inches) ................................................................. 72

B.1 Fundamental Natural Frequencies and Viscous Equivalent Damping Decrements (δ) for SRMS Reference Position #1 (Maneuver 1) ................................................................. 83
B.2 Fundamental Natural Frequencies and Viscous Equivalent Damping Decrements (δ) for SRMS Reference Position #1 (Maneuver 2) ................................................................. 89
B.3 Fundamental Natural Frequencies and Viscous Equivalent Damping Decrements (δ) for SRMS Reference Position #1 (Maneuver 3) ................................................................. 94
B.4 Fundamental Natural Frequencies and Viscous Equivalent Damping Decrements ($\delta$) for SRMS Reference Position #1 (Maneuver 4) ........................................ 99
B.5 Fundamental Natural Frequencies and Viscous Equivalent Damping Decrements ($\delta$) for SRMS Reference Position #2 (Maneuver 1) ........................................ 102
B.6 Fundamental Natural Frequencies and Viscous Equivalent Damping Decrements ($\delta$) for SRMS Reference Position #2 (Maneuver 2) ........................................ 105
B.7 Fundamental Natural Frequencies and Viscous Equivalent Damping Decrements ($\delta$) for SRMS Reference Position #2 (Maneuver 4) ........................................ 111
B.8 Fundamental Natural Frequencies and Viscous Equivalent Damping Decrements ($\delta$) for SRMS Reference Position #3 (Maneuver 1) ........................................ 114
B.9 Fundamental Natural Frequencies and Viscous Equivalent Damping Decrements ($\delta$) for SRMS Reference Position #3 (Maneuver 2) ........................................ 117
B.10 Fundamental Natural Frequencies and Viscous Equivalent Damping Decrements ($\delta$) for SRMS Reference Position #3 (Maneuver 3) ........................................ 122
B.11 Fundamental Natural Frequencies and Viscous Equivalent Damping Decrements ($\delta$) for SRMS Reference Position #3 (Maneuver 4) ........................................ 127
Chapter 1

Introduction

Effective tracking control of structurally flexible manipulators is of increasing concern particularly in space robotic and telerobotic applications. The original design specifications on space manipulators required large reach envelopes and low launch weight. These initial constraints have been increasingly joined by demands for higher manipulator speeds and improved positioning capability. Higher speeds coupled with long-reach and low-weight manipulators; however, result in substantial elastic deformation in linkages and joints during maneuvers. For example, the Shuttle Remote Manipulator System (SRMS) displays a large degree of structural flexibility even at joint speeds considered quite slow in conventional industrial robotic applications.

The application of large flexible manipulators is by no means limited to space, although it is in this implementation that the constraints are the most severe. Such manipulator systems are also the focus of considerable attention in forestry and in the construction industry, although with less constraint on the positioning tolerance in these applications. Most recently, large robotic manipulators have been recognized as an integral part of the hazardous-waste clean-up effort in the United States; it is conservatively estimated that this effort will be a multibillion-dollar industry by the turn of the century.

The utilization of robotic manipulators in these and other applications, however, has been hampered by the availability of successful and versatile control methods. Speed, as has already been mentioned, is a major issue. The elas-
ticity in the links and joints (as a result of the gearing) of large manipulators makes control in point-to-point maneuvers or end-effector trajectory tracking quite challenging. The established means by which end-effector trajectory tracking was accomplished, namely, with control laws which cause the joints to follow a prescribed trajectory, are generally unfit for flexible manipulators.

Visual Servoing. Visual servoing is the use of visual information (features) to control the location and orientation (position) of a manipulator’s end-effector [Hashimoto, 1993]. The image sensor (usually a video camera) may be fixed with respect to the workspace or mounted on the manipulator itself (usually near or on the end-effector for better views of the task space). The simplest form of visual sensing for manipulation is position-based “look-and-move” in which the visual sensing is used in an open-loop manner to provide information for the subsequent motion. Visual servoing, on the other hand, provides positioning data directly to the controller for use in determining the required joint motions.

The use of visual information is extensively documented in the literature aimed towards the guidance of autonomous vehicles, robotic manipulators and mechanisms. In most instances, the control structure is one of dynamic look-and-move in which the visual information provides position data which is then used by a controller to move an actuator. This approach is motivated by, but is different than, the natural facility which humans employ in what is commonly termed “hand-eye coordination.” In this case, vision and joint data is strongly integrated in the control of limbs; it is elucidating to term this “vision-assisted servoing.” Vision-assisted servoing can be seen as a hybrid of joint servoing and the positioning of autonomous machines and manipulators using only visual information.

Flexible-Manipulator Control. Considerable effort has been directed towards the control of structurally flexible manipulators, much of which has focused on single link systems. Several approaches have been proposed for large flexible systems; these have included shaped command inputs, feedforward and inverse-dynamics techniques, and hybrid approaches.
Carusone, Buchan and D’Eleuterio [Carusone et al., 1989] have developed a multilink control strategy which employs strain measurements in a fully feedback-driven technique based on optimal control theory and "gain scheduling." In essence, the procedure consists of scheduling gains using a series of steady-state linear regulators. But, in addition, the state description of the system is augmented to include the torque inputs and their first derivatives in the state. This has the effect of smoothing out the torque control inputs to the manipulators; jagged torque inputs are very often the main source of vibration disturbances.

This control technique has been successfully implemented in computer simulation for a two-link planar structurally flexible manipulator system and the computer results have been verified experimentally [Carusone et al., 1990] using Radius—the Space Robotics Laboratory Facility established at the University of Toronto Institute for Aerospace Studies. Since the Radius facility utilizes metal foil strain gauges, we can draw an analogy to visual servoing and refer to this type of control as "strain-assisted servoing." The procedure has also been successfully implemented on a computer simulation model of Canadarm, demonstrating that it is indeed an effective control method for three-dimensional structurally flexible manipulators [Carusone and D’Eleuterio, 1993].

The Motivation for Using Machine Vision. To date, most research into the feedback control of structurally flexible manipulators has assumed that the dynamics of a given manipulator would be measured by instrumenting the linkages and/or joints with accelerometers or strain gauges to supplement the data from the joint encoders. For many applications, however, where the workspace is structured but not necessarily known, as in the case of space applications, or where the environment is quite unstructured, as in the case of hazardous-waste clean-up, these types of sensor alone will not suffice. It shall be necessary to monitor the workspace, the position and orientation of objects and obstacles, continuously and to integrate this knowledge directly into the control system. This capability is most effectively afforded by the use of machine vision sensors.

Experiments performed in orbit [Goodwin, 1992] indicate that substantial amounts of information about low-frequency vibrations can be determined
from video data. An in-depth exploration and discussion of this on-orbit
data is undertaken.

An exhaustive search of the literature shows that only one published attempt
has been made which takes advantage of the temporal sampling afforded
by machine vision to provide feedback to a dynamic mechanism. However,
Wang [Wang, 1986] had theorized that such an approach might be feasible
for use with a space-borne antenna. Wang suggested that, by using the
intensity data from the reflective surface and a suitable reflectance model,
it was possible to estimate the position and velocity of the surface from a
sequence of camera images. Wang also suggested the use of special markings
to provide a baseline from which surface motion could be estimated by use
of the image of the deformed markings.

**Overall Objective.** It is therefore the overall objective of this project:

To establish the feasibility of using machine vision for control of a flexible
manipulator and to establish a method for supplying position feedback infor-
mation to a structurally flexible manipulator control system by integrating
a high-performance machine vision system into the servo loop.
Chapter 2

Background

This project centers on the possible use of machine vision in feedback control of flexible manipulators and as such it is necessary to study the aspects of various approaches to develop an effective and practical technique. While machine vision has not been used for this purpose in the past, there exists a number of studies and techniques which indicate that such an approach is feasible.

Photogrammetry. The photogrammetric method is well understood and provides the basis for the Space Vision System (SVS). The SVS is primarily a position sensor which relies on an array of target features affixed to the payload. As a photogrammetric machine vision system, the SVS also uses an innovative, and patented, on-line video sampling process to determine the centroids of targets accurately in real-time [Pinkney, 1978]. Employing a priori knowledge of the geometry of the target, the SVS can compute the x-y-z position and the pitch-yaw-roll orientation of the target, as well as the associated rates, with respect to any specified coordinate system. Component motions are decoupled by the system processor to facilitate single-axis control, but six-degree-of-freedom displays allow simultaneous control of both position and attitude. The SVS was flown on the Space Shuttle mission STS-52. Chapter five includes a complete description of the function of the photogrammetric platform and the design parameters imposed by the measurement of the image features.
The Advanced Space Vision System (ASVS) is a hybrid system employing the best features of both an on-line processor and a framegrabber. The ASVS encompasses all the capabilities of the SVS, plus additional capabilities of subsequent development of both software and hardware. Improved processor speeds have dramatically expanded the capability of the ASVS; more mathematically rigorous photogrammetric algorithms and increased data handling speeds have permitted ASVS to become more flexible and more robust in its operation.

Neither the SVS nor ASVS has been integrated into the control loop of a robotic manipulator system. (On STS-52, for example, the SVS was used primarily to characterize the Canadarm.) However, the capabilities of these systems ideally lend themselves to such an integration and a purely kinematic robot controller has been demonstrated with the laboratory-grade precursor to the SVS (this demonstration was conducted by NRCC in the mid-1980's for a potential Orbital Maneuvering Vehicle (OMV) contractor in their facilities and has not been documented formally). In fact, a photogrammetric vision system would find the greatest usefulness if integrated fully with the camera control system and with the manipulator control system.

**The Radius Experimental Facility.** The evaluation of any control algorithm/approach requires definitive testing on a real system. The Space Robotics Group at the University of Toronto Institute for Aerospace Studies has established the *Radius* facility (Figure 2.1) in response to the need for an experimental testbed for the validation of dynamics models and control methods for structurally flexible multilink systems. *Radius*, in its baseline configuration, is a two-link planar manipulator with rotary joints supported by airjets. The design is modular: Links can be easily interchanged and/or added; an end-effector, in fact, which may be used as a third link exists for the facility. Moreover, *Radius* can be configured to behave dynamically like a two-dimensional version of SRMS.

**ASVS Platform.** Neptec Design Group of Ottawa is under contract to CSA to develop the ASVS platform. Under an agreement which protects the intellectual property of all participants, an ASVS unit has been made available to UTIAS for use with the *Radius* facility.
An unloaded SRMS has a lowest natural frequency of approximately 0.5 Hz, although this will vary with both payload mass and arm configuration. The *Radius* facility can be configured to have natural frequencies in this range. The update rate of the ASVS is 30 Hz and the system latency is 50 ms; so it is reasonable to propose that the ASVS can provide adequate data to control *Radius* when configured to mimic the lowest natural frequencies of the SRMS.

It has been demonstrated previously that a human operator can use the real-time data from the SVS to improve the dynamic performance of a manipulator. Operators using the SVS with a full-scale hydraulic training version of the SRMS (Manipulator Development Facility—MDF) and with a full-beam flexure computer model of the SRMS (Systems Engineering Simulator—
SES), both at the NASA Johnson Space Center, demonstrated a capacity to accommodate both stiction related cross-coupling and oscillation due to linkage flexure. That humans, aided by a real-time analytic tool, can account for the large amplitude oscillations in such a complex system bodes well for both modern and neural-network-type controllers.

The development of a vision control system using photogrammetry will first be based on the ASVS using manipulator end-effector trajectory tracking (MEETT). The procedure will be extended to incorporate the vision data from the ASVS. The ASVS sensor measurements will be fed back in real-time and incorporated into the current structure of the controller. Thus, it will provide vision-in-the-loop control.

At present, MEETT can run successfully at an update rate of 100 Hz. Faster rates, of course, would produce better performance. The ASVS, however, nominally operates at 20 to 30 Hz. Therefore, estimation techniques will have to be employed to infer an effective rate of 100 Hz.

The laboratory system requires a functional design of target array(s) suitable for use with the *Radius* facility. This design is dependent on manipulator geometry, camera location(s), and operational philosophy.

Proper behavior of the vision system requires a verification of solution stability from the ASVS. This is dependent, among other things, on lighting, the velocity of target array projection in the image plane and tracking filter coefficients. Transducer characterization of the vision system is fundamental to including it in the control model.

The ASVS, in its current configuration, is designed to provide graphical position data (in the form of synthetic views and attitude gauges) for use by a human operator. A key component of this study will be the integration of code into the SVS which will allow the photogrammetric solutions to be extracted in real-time for use by the manipulator controller. The challenge in this case is to implement the code in such a way that it doesn’t interfere with the tight task scheduling that exists within the ASVS coding. The insertion of this output task and its effects on task scheduling are of interest for the final testbed implementation.
An important aspect of the photogrammetric investigation is the analysis of suitable control philosophies. Classical and modern control concepts will be the first evaluated, and a good deal of weight will be given to the control strategies already employed on the *Radius* facility. As the photogrammetric study progresses, appropriate areas for artificial neural-network control will be noted. It is possible that a hybrid system where the vision measurement provides very precise data as input to a neural network-type trajectory controller may be very effective. For this reason vision-assisted servoing is used as the baseline for the laboratory implementation, but care is taken not to preclude the possible use of pure visual servoing techniques in the future.
Chapter 3

Project Definition

This project has three stages; analysis of on-orbit flight data, laboratory testbed implementation and characterization of integrated testbed.

3.1 Flight Data Analysis

An important step in this investigation is the evaluation of the STS-52 Shuttle Flight data. The analysis of this data will help us determine both the suitability and the real-world limitations of machine vision in this application.

It is essential that an understanding of what can reasonably be accomplished with machine vision in the field of dynamics and velocity control. Furthermore, this investigation may indicate what supplementary study might need to be done on future flights with larger payloads. There are other limitations in the space environment as well; the most notable limit for machine vision is lighting. In the case of lighting, for example, it must be determined to what degree signal conditioning can improve the image “after the fact” and how much improvement must be made on the scene viewed by the camera. The latter improvement would likely require costly improvements on the transducer, peripheral devices, or on operations. The signal processing costs are limited to the production and validation of algorithms/software and would
be greatly preferred. While ordinary kinematic control of a manipulator will define these limitations, the dynamic behavior of the manipulator may well determine the safety margin within these limitations.

It is rare that well-conditioned vision data from low earth orbit is available for study. Excellent data is available from the STS-52 mission in 1992, and is used here to explore the degree of difficulty associated with using cameras and machine vision in the harsh variable lighting in low earth orbit (LEO).

Figure 3.1: Arm Configurations for STS-52 Dynamics Experiments (SVS-9).

The SVS photogrammetry database from STS-52 was produced by the Institute for Advanced Manufacturing Technologies (IAMT) at the National Research Council of Canada (NRCC) in Ottawa. Data from Flight Day Six of STS-52 was collected from a demonstration of real-time measurement of dynamic structural deflections (or vibrations) using the SVS. In this test,
called SVS-9, the crew caused vibrations in the SRMS by driving one joint to maximum speed and then applying the brakes. This test was done for three different arm configurations; two configurations (Figures 3.1a and 3.1b isolated primarily linkage bending modes or torsional modes, the third configuration (figure 3.1c represented an average of the first two configurations). In all three configurations, the shoulder yaw and elbow pitch joints were excited separately to isolate different vibration regimes.

3.2 Laboratory Implementation

Theoretical work in machine vision is always hampered by the complexities of the lighting and perspective modeling. Only implementation on a real world testbed will provide the imaging nonlinearities and irregularities required to fully challenge the vision system. Prior to this work, Radius had all the infrastructure of a manipulator testbed, so the additional requirements were that the ASVS and the collateral target arrays, cameras and lights be integrated into the existing testbed.

The laboratory system required a functional design of target array(s) suitable for use with the Radius facility. This design was dependent on manipulator geometry, camera location(s), and the operational philosophy.

A grayscale camera was selected from a commercial distributor. The camera was chosen to meet criteria favored by ASVS's flavor of image processing. A collocated lighting source was constructed to produce even lighting throughout the image.

The tightly constrained real-time code of the ASVS required modifications to permit the communication of the photogrammetric solutions to the control computer at video rate. A solution was found which did not interfere with the photosolution process tasks.

Proper behavior of the vision system requires a verification of solution stability from ASVS. This will depend on lighting, tracking filter coefficients, and the velocity of the target array projection in the image plane. A number of laboratory configurations were required to optimize the photosolution behavior.
3.3 Characterization

With ASVS integrated into Radius, it became essential to understand the behavior of the vision feedback during a manipulator operation. A number of parameters are required for producing good optimal controllers; a characterization of the ASVS and support equipment was deemed necessary.

- Camera lens/scan calibrations were performed at the NRCC laboratories in Ottawa to provide look-up tables for ASVS error correction routines.

- An important parameter in a transducer is latency. Tests were conducted to measure the time delay between object motion and ASVS output of that motion.

- The sampling rate of a measurement system is crucial to the construction of a viable controller. The update rate of the ASVS was tested rigorously to ensure that it was producing repeatable and consistent sampling rates.

- Tests were conducted to ensure that ASVS was giving sufficient fidelity of measurement. Tests of this nature test all aspects of the ASVS built-in calibration routines as well as the applicability of the camera lens calibration to the focal range of the camera/lens assembly.

The methodology pursued for this analysis, implementation, and characterization is described more completely in the following three chapters.
Chapter 4

Flight Data Analyses

The CANEX-2 series of experiments were conducted during the STS-52 flight of the NASA Space Shuttle Orbiter in October of 1992. A major constituent of the CANEX-2 experiments was the characterization of the Space Vision System (SVS), a machine vision system developed by the National Research Council of Canada (NRCC) [MacLean and Pinkney, 1993]. In particular, one of the SVS experiments used the Canadarm (Shuttle Remote Manipulator System or SRMS) and an array of targets on a Canadian payload to measure the oscillations induced in the SRMS by the direct application of current to the joint motors. This chapter comprises linear and nonlinear analyses of the SVS data from this experiment and seeks to identify the elastic and damping factors of the experimental configurations of the SRMS for comparison with theoretical models.

The SVS experiments on STS-52 were not the first instance in which SVS photogrammetry technology was utilized to measure the response of the SRMS to exciting forces. Videotape of SRMS backup mode testing was collected on shuttle mission STS-3 in March of 1982 [Basso and Kulchyski, 1983] [Basso and Kulchyski, 1984]. No pre-launch arrangements were made for the collection of this video data which was a straightforward video camera recording of a test comprising a shoulder pitch maneuver to induce oscillatory motion. Natural features evident in the resulting video were used to define suitable targets from which to assess photocoordinate data. The analog video signal was preprocessed to enhance the signal sufficiently to use the SVS to
analyze in this indirect mode of operation. These studies demonstrate the feasibility of using SVS techniques to extract dynamical data from on-orbit events. The absence of prelaunch preparations limited the detailed information that could have been obtained. Consideration was therefore given to implementing the prerequisite experimental structure for the STS-52 experiments.

The STS-52 flight experiment was developed by the Institute for Aerospace Research at NRCC in collaboration with NASA and the Canadian Astronaut Program. This study makes use of the SVS photogrammetry database originating from the Institute for Advanced Manufacturing Technologies (IAMT) at the NRCC in Ottawa [Perratt et al., 1994]. The documentation accompanying this database contains an excellent discussion of the experiment and its protocols.

Data from Flight Day Six of STS-52 were collected from a demonstration of real-time measurement of dynamic structural deflections (or vibrations) of the SRMS using the SVS. In this test, the crew caused vibrations in the SRMS by driving one joint to maximum speed and then applying the brakes. This test was done for three different arm configurations (seen earlier in Figure 3.1); two configurations primarily isolated linkage bending modes or torsional modes, the third configuration represented an average of the first two. SRMS joint encoder data were collected in addition to the three-dimensional target position data measured by the SVS. Unfortunately, inaccurate time-tagging and a lower than anticipated sampling rate rendered the SRMS joint encoder data useless for a dynamic analysis.

The reviewed SVS data was provided digitally in a number of raw and preprocessed formats. Coordinate transformations and digital signal analysis techniques were then applied to the SVS-produced data to identify the elastic and damping factors of the SRMS. The ultimate goal of these analyses is an identification of SRMS system parameters for the three experimental configurations for comparison with theoretical models.
CHAPTER 4. FLIGHT DATA ANALYSES

4.1 Flight Data Handling

4.1.1 Raw Data

SVS Dataset. The preprocessed data was provided digitally in a number of formats. The category used for the linear study was the 'transformed graphics' data, which is derived from the 'basic' solution which is then transformed to the SVS reference coordinate system. The 'basic mean' category,
in turn, is derived from the 'raw' category by filtering with SVS database resident filtering coefficients. Figure 4.1 shows a plot of a sample dataset of 'transformed graphics' data.

It proved beneficial to use the 'raw' category for the nonlinear analyses so that more control could be exercised during the filtering stage. The 'raw' solution is a nonfiltered solution derived from corrected photocordinates and the (feedback filtered) rotation matrix. The SVS-9 Data Release [Perratt et al., 1994] provides a discussion of the data handling and a complete description of the raw database.
### SRMS Dataset

Figure 4.2 shows a plot of SRMS data plotted simultaneously with SVS data from the same maneuver as that in Figure 4.1. Note that the SRMS data appears in 'pairs' and that it lags the SVS data. Both effects arise from the same source; that is, the data transfer to the General Purpose Computer (GPC) from the Manipulator Controller Interface Unit (MCIU).

Most of the data from the arm-based electronics and the MCIU enters the GPC via the launch data bus, LDB1. While some arm parameters go to the Operational Instrumentation (OI) first and are then relayed to the GPC via the Pulse Code Master Measurement Unit (PCMMU), several critical arm parameters are transmitted directly to the GPC. These parameters include the end-effector talkbacks (on/off indicators), arm mode indication, and the joint encoder angles. The GPC reads these critical parameters (and for other
critical systems, e.g., OMS, IMU, RCS) from a buffer and time tags them with Greenwich Mean Time from the main clock. The apparent time delay in the data is due to the latency period between the loading of the MCIU memory and the time tagging created by the GPC prior to the passing of the values to the PCMMU for downlink. The GPC blocks all of the data parameters into a GPC downlist format and then makes it available to the PCMMU for downlink. The volume of downlinked data is dependent upon the (programmable) bit rate and the telemetry format load (TFL). While the PCMMU downlinks data at a programmable rate, the actual limit is imposed by the rate at which the GPC reads data from the MCIU.

In the case of the SVS-9 data downlink, the GPC was reading/writing all databuffers with an approximately 2.0 second lag at about 0.5 Hz and the PCMMU was downlinking these values at 1.0 Hz (Figure 4.3). This led to both the data pairing and to the apparent lag. There is no clear-cut method of correcting for the data lag, short of empirical measurement of the GPC read/write rates for an identical TFL. Furthermore, the low sampling rate of the SRMS data makes it unrewarding to attempt a correction for this particular experimental analysis.

4.2 Linear Analysis

4.2.1 Purpose

This section provides a foundation for a thorough low-frequency system identification of manipulator vibrational data, measured by the SVS, for the three arm configurations of the SRMS. This section provides a treatment of the SRMS as though it were a linear system, but sets the stage for a more complete analysis to account for substantive nonlinearities which are clearly present in the data.
4.2.2 Scope

The scope of this section is limited to a determination of the dynamic structural characteristics of the SRMS to the extent that they match a linear representation of the dynamic behavior of the SRMS.

4.2.3 Data Handling

This subsection outlines the methodology used for the linear analysis of the SVS-9 dataset. Each subsubsection discusses a stage of the data processing starting with the windowing, a derivation of the natural damped frequency, and ending with the determination of the damping coefficient.

Transformation to the SRMS Pitch Plane

With the exception of the wrist roll joint, all of the SRMS joints lie within the pitch plane of the manipulator. The pitch plane of the SRMS is the plane containing the upper and lower arm booms of the manipulator (since the shoulder and wrist pitch joints are all adjacent to the elbow pitch joint, this plane is normal to all the pitch joint axes of the manipulator). It is helpful to take advantage of this in performing dynamic analyses because the dominating vibration modes have motions either in, or orthogonal to, the pitch plane. The motions can be effectively decoupled by transforming the oscillations into the frame of the pitch plane at the shoulder yaw joint. Pitch joint excitations, in particular, demonstrate motions which are almost completely confined to the pitch plane. Shoulder yaw excitations, on the other hand, produce vibrations which occur orthogonal to the pitch plane. Figures 4.4 and 4.5 show the pitch plane and phase between the OBAS X-Y-Z directions during a typical vibration caused by a driven pitch joint; the resulting motion is largely in the manipulator pitch plane.
Figure 4.4: Pitch Plane and phase between OBAS X and OBAS Z Oscillations

Windowing

The selection of ranges or regions of data to be processed is termed "windowing". For this analysis, the data windowing was accomplished by inspection. A facility was included in the file structure to allow selection of a user-configurable start and end frame of the dataset. This step was required because there is no analytic method of determining when the brakes on the driven joint were engaged. This windowing defines the particular area where free vibration is occurring. This prepares the data for the next stage of processing, *detrending*. 
Chapter 4. Flight Data Analyses

Figure 4.5: Pitch Plane and phase between OBAS Y and OBAS Z Oscillations

Mean Detrending

Detrending is the removal of the mean value or linear trend (or even higher order trends) from a vector or matrix. This step is required to identify the equilibrium position about which the vibration occurs. Initially, this stage was accomplished with a fast Fourier transform (FFT), zeroing the DC offset, and then performing an inverse FFT. This was changed to the more efficient MATLAB detrend function which would allow for linear in addition to mean detrending. Linear detrending removes the best straight-line fit from the data vector. Mean detrending removes just the mean value.
from the data vector. Mean detrending was used at this stage; the option of a linear detrend was exercised at a later stage of processing. The basic MATLAB detrend was augmented to allow for small biases to be added to the mean and linear detrend coefficients. This augmentation was required to counteract the processing difficulties resulting from the small number of oscillations produced by the free vibration of the SRMS.

![Bode Plot of 12th Order Butterworth Low-pass Filter](image)

**Figure 4.6**: Bode Plot of 12th Order Butterworth Low-pass Filter.
Low-pass Butterworth Filtering

The next stage of processing was the Butterworth digital filter design. Since the filter can be applied to the data in nonreal-time, a high-order low-pass filter was designed to isolate the fundamental structural modes from the signal. A Butterworth filter is maximally flat in the bandpass region and monotonic overall. A 12th order filter was used to produce steep roll-off characteristics without producing truncation errors in the processor. Figure 4.6 shows a Bode plot of the attenuation magnitudes of the passband and stopband of this filter; the phase plot is not of interest in this instance since a zero-phase forward and reverse digital filtering was applied using this filter (i.e., the sequence is reversed and run backwards through the filter resulting in zero phase distortion and double the filter order). Initial conditions are matched to avoid startup and ending transients. The cutoff frequency was set to 2.0 Hz to ensure a good logarithmic decrement profile for the fundamental frequency.

Linear or Mean Detrending

A second detrend stage is used at this point to allow for linear detrending to also be accomplished as desired. Since most of the vibration amplitude remained in the passband of the filter, the mean portion of the detrend did very little at this stage. Linear detrend was applied where appropriate.

Power Spectral Density

In order to identify the frequency of the fundamental modes, it is necessary to produce a power spectrum estimate of the data sequence. The estimate of the power spectral density (PSD) of the signal vector was made under MATLAB using Welch's averaged periodogram method [Oppenheim and Schafer, 1989]. This was done for both the detrended vector, and for the detrended and filtered vector. In this procedure, the signal was divided into overlapping sections. The sections are windowed (Hanning), transformed with an FFT, and accumulated. The power spectrum was then plotted for frequencies up to half the sample rate of 15.0 Hz (the Nyquist frequency).
Logarithmic Decrement and Linear Fit

A useful method for determining the amount of damping in a system is to measure the rate of decay of free oscillations. Clearly, the larger the damping present, the greater the rate of decay observed. If \( s_1 \) and \( s_2 \) are successive peaks of a free oscillation separated by time \( \tau_d = \frac{2\pi}{\omega_n \sqrt{1 - \zeta^2}} \), the logarithmic decrement is defined as:

\[
\delta = \ln \frac{s_1}{s_2}
\]

For a damped vibration of the general form:

\[
x = X e^{-\zeta \omega_n t} \sin(\sqrt{1 - \zeta^2} \omega_n t + \phi)
\]

the value of \( \delta \) becomes:

\[
\delta = \ln \frac{e^{-\zeta \omega_n t_1}}{e^{-\zeta \omega_n (t_1 + \tau_d)}} = \zeta \omega_n \tau_d
\]

substituting for \( \tau_d \):

\[
\delta = \frac{2\pi \zeta}{\sqrt{1 - \zeta^2}}
\]

If \( n \) cycles of the oscillation are used, the logarithmic decrement becomes:

\[
\delta = \frac{1}{n} \ln \frac{s_0}{s_n}
\]

This can be interpreted graphically as the slope of a line passing through the peaks of a plot of \( \ln x^2 \) (or \( \ln y^2 \) or \( \ln z^2 \)). Figure 4.7 shows this plot for a typical SRMS maneuver. Because of the obvious nonlinearities of the arm behavior, a facility was incorporated into the algorithm to allow the analyst to choose the number of peaks used to determine the equivalent damping coefficients. In addition, the low-pass filter stage prevented high-frequency components from generating peaks which could not be properly handled by the linearized treatment.
4.2.4 Flight Data Analyses

Figure 4.7: Linear Least-Squares Fit to a Typical Logarithmic Decrement Plot

Analytic Assumptions. In these analyses, a number of assumptions have been made to facilitate the basic understanding of the SRMS dynamic behavior. For this part of the analysis, the SRMS/CCTV/SVS were assumed to have the following attributes:

- The SRMS is a linear system.
- The sampling rate of the camera is high enough to preclude signal aliasing.

- The majority of the frequencies which produce substantial deflection are below $\frac{1}{10}$ of the Nyquist frequency.

For this part of the analysis, the SRMS was treated as a linear system. In particular, the damping of the manipulator was assumed to be proportional to the arm velocity (i.e., fits a viscous damping model).

The 30-Hz sample rate of the camera is taken to be higher than any of the natural frequencies which affect the function of the SRMS (i.e., it causes deflections to within four orders of magnitude of what the joints themselves can produce). In a sense, the signal arriving at the camera is bandlimited because the mechanical system does not produce large amplitudes at high frequencies. The issue of signal aliasing for this manipulator is not a concern despite the low sampling frequency of the camera.

Sample Analysis. Figure 4.8 shows the photogrammetric measurement of one of the SVS-9 oscillations. It should be noted that the vibration in this test is nearly confined to one plane (the plot shows the three components projected onto this plane). The principal oscillation, following a simple linear detrending, is shown in Figure 4.9; it is noteworthy that the vibration appears to undergo a transition from one vibration regime to another. Figure 4.10 shows a least-squares fit to the linearized logarithmic decrement; the slope of this line indicates the degree of damping. Hence, for this configuration, a second-order damping coefficient can readily be determined, in addition to the fundamental frequency in the plane of the motion. In this case, we find a second-order damping coefficient of $\zeta = 0.029$ and a period of 4.2 seconds (corresponding to a frequency of 0.24 Hz). Again, note should be made that the analysis suffers from the inability to properly detrend the oscillation over the transition. The result is an inaccurate poor solution in the low amplitude regime of the vibration (the high amplitude initial vibration tends to dominate the detrending).

Figure 4.11 shows the power spectral density of the oscillation and the density of the signal after filtering at 30% below the Nyquist frequency of the
measurement. The dominant amplitudes (by three orders of magnitude) fall below the filter cut-off. A second peak, probably the second harmonic, can be seen at twice the frequency of the first; this mode might become interesting in a forced oscillation, but produces little motion in the unforced case. There is also a small peak at 10 Hz which is visible in all the maneuvers. The frequency is 1/3 the camera frame rate, so it is possible that it is an aliasing effect. Since the amplitude is small and since the frequency is above the Nyquist limit, this effect will not be investigated further in this document.

All maneuvers were treated similarly. Each dataset followed the same stages of processing as described in the previous subsection. A special transformation vector was implemented for each maneuver to specify the windowing, the pitch-plane transformation, the detrend level, the filter order, and the number of peaks used for the decrement fitting. The results for a typical maneuver are presented in the next subsection.

SRMS Position #1

Maneuver 1.1

This oscillation resulted from a direct-drive current to the SRMS shoulder yaw joint with the arm configuration shown in figure 3.1a. Note that in this drive mode, with the exception of the driven joint, all the joint brakes are fully engaged. The results of the analysis are summarized in Table 4.1.

Table 4.1: Fundamental Natural Frequencies and Viscous Equivalent Damping Decrements for SRMS Reference Position #1 (Maneuver 1)

<table>
<thead>
<tr>
<th></th>
<th>X-Axis</th>
<th>Y-Axis</th>
<th>Z-Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>0.237</td>
<td>0.237</td>
<td>0.237</td>
</tr>
<tr>
<td>Frequency (rad/s)</td>
<td>1.49</td>
<td>1.49</td>
<td>1.49</td>
</tr>
<tr>
<td>Damping Decrement, δ</td>
<td>-0.029</td>
<td>-0.022</td>
<td>-0.008</td>
</tr>
</tbody>
</table>
Figure 4.8: SVS-9 Maneuver 1-1 (3 Axes) with Roll 19.48 and Yaw 8.4
4.2.5 Concluding Remarks - Linear Analysis

The amplitudes of vibration measured in the SRMS are dominated by frequencies in the Nyquist limit of a 30 frames per second video camera (Figure 4.11). This lends confidence to the concept that a sufficient amount of data can be retrieved via standard video cameras to warrant designing a controller. The variation of natural damped frequency, however, indicates that further study of the photogrammetry data is merited. In particular, techniques that preserve the nonlinear characteristics of the vibration need to be employed to determine the deviation of the oscillation from that of a linearized model.

Figure 4.9: SVS-9 Maneuver 1-1 (X Axis) with Roll 19.48 and Yaw 8.4
Table 4.2: Fundamental Natural Frequencies and Viscous Equivalent Damping Decrement s for SRMS Reference Position #1 (Maneuver 1) determined via Hilbert Transformation

<table>
<thead>
<tr>
<th></th>
<th>X-Axis</th>
<th>Y-Axis</th>
<th>Z-Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>0.237</td>
<td>0.237</td>
<td>0.237</td>
</tr>
<tr>
<td>Frequency (rad/s)</td>
<td>1.49</td>
<td>1.49</td>
<td>1.49</td>
</tr>
<tr>
<td>Damping (initial)</td>
<td>-0.0121</td>
<td>-0.0110</td>
<td>-0.0070</td>
</tr>
<tr>
<td>Damping (post-transition)</td>
<td>-0.0094</td>
<td>-0.0090</td>
<td>-0.0011</td>
</tr>
</tbody>
</table>

Figure 4.10: Logarithmic Decrement Plot - SVS-9 Maneuver 1-1 (X Axis)
4.3 Nonlinear Analysis

4.3.1 Purpose

This section provides a more in-depth low-frequency system identification of the three arm configurations used in SVS-9. This section treats of the SRMS behavior as though it were nonlinear. The characteristics of the oscillations revealed in the linear analysis was used to define multiple windows for this nonlinear analysis.
4.3.2 Scope

The scope of this section is a determination of the dynamic structural characteristics of the SRMS and to investigate how much variance exists between linear and nonlinear representations of the dynamic behavior of the SRMS.

4.3.3 Multiple Windowing

Because all of the measured oscillations showed that the SRMS has a transition from one vibration regime to another (Figure 4.12), it became important
to isolate the regimes to determine how the stiffness and damping changed following the transition. A structure was introduced in the analysis modules to permit analyses of temporal subsections of the vibrations (Figure 4.13). This allowed for an isolation of the oscillations before and after the apparent transition. In this way, the stiffness and damping coefficients could be determined before and after the transition.

Figure 4.13: Multiple Windowing of Vibration Data
4.3.4 Hilbert Space Analyses

The largest single change in this analysis over the previous is the use of the Hilbert transform, a transformation that is proving useful in modern system identification methods. The Hilbert transform translates a given signal by a quarter period and rotates the transformed signal into the imaginary plane. This transformation is accomplished using an FFT method to determine the periodicity of each frequency band. The signal, combined with the Hilbert transform of the signal, now describes a spiral signal in the complex spacetime.

While the imaginary portion of this spiral signal is the actual Hilbert transform, the combined signal is also commonly referred to as the Hilbert transform of the original signal; this report will make use of this less precise nomenclature because there is no ambiguity in the current implementation. Figure 4.14 shows the photogrammetric measurement of one of the SVS-9 oscillations transformed via the Hilbert transform.

In order to avoid start-up transients, the Hilbert transformation was performed on a modified digital signal. The original signal was preconditioned via windowing and detrending. A copy of the signal was then mirrored and inverted and added to the start and end of the original preconditioned signal. This results in a signal resembling a “wave packet” as shown in Figure 4.15. This resultant signal was digitally filtered using a Butterworth filter to remove frequencies above the Nyquist frequency and was then Hilbert transformed. The natural logarithm of the square of the magnitude of this final signal correlates to the logarithmic decrement of the linearized analysis. In this case, however, every data point of the measured signal is used to determine the damping coefficients of the system. This allows for a determination of the deviation of the system from a linear approximation. Figure 4.16 shows the correspondence between the logarithmic decrement and the Hilbert transformation approach. Again, the slope of the Hilbert transform generated curve corresponds to the degree of damping throughout the oscillation.

Hence, a second-order damping coefficient can again be determined; in this case the temporal variation of this coefficient can also be determined.
4.3.5 Concluding Remarks - Nonlinear Analysis

The measured frequency of the fundamental mode (Table 4.2) correlates well with the mathematical models response at the low-hover position and at the unberthing arm configuration (these models have been verified with on-orbit accelerometer data [Gray et al., 1985]). Not the different coefficients of damping before and after the transition in the vibrational behavior of the manipulator system. Little experimental data are available to validate the
damping coefficients measured for the SVS-9 arm configurations, however. The transition in the vibrational behavior at low amplitudes has certainly not been accounted for in any documented model.

It would appear from the on-orbit data that machine vision is a suitable transducer for the extraction of large-amplitude arm dynamics from the SRMS. Indeed, machine vision shows a good deal of promise as a system identification tool for such dynamics.
4.4 Comparison with Ground Testbed

A complete understanding of the differences between the SRMS and the Radius facility can only be gained by a comparison of the dynamic behavior of the two manipulators. Since the data available for the SRMS is limited to that measured by the SVS-FM on-orbit, a similar experiment was undertaken with the Radius manipulator using the ASVS on the ground.
Table 4.3: Fundamental Natural Frequencies and Viscous Equivalent Damping Decrements for **Radius** Comparative Test

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>0.242</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (rad/s)</td>
<td>1.52</td>
</tr>
<tr>
<td>Damping Decrement, $\delta$</td>
<td>-0.0609</td>
</tr>
</tbody>
</table>

Projections were used in the case of the three-dimensional oscillations of the SRMS to effectively decouple the motion with respect to the pitch plane of the manipulator. In the case of oscillations of the **Radius** manipulator, the presence of the air-bearing surface constrained the oscillations to be in the pitch plane. Measurements of these oscillations proved to be problematic with the poor response time and low sampling rate of the ASVS emulator available. However, following substantial experimentation with near-ideal lighting conditions, usable data were collected.

An impulse was imparted to **Radius** by preloading the arm booms (by deflecting the end effector) and releasing the preload after the vision targets had been acquired by the ASVS and tracking initiated. Figure 4.17 shows the unfiltered response of **Radius** following the application of the impulse. An examination of envelope functions around the data showed reasonable correlation between the observed damping and a viscous damping model. A Hilbert-Space analysis was used to determine the logarithmic decrement of the vibration; Figure 4.18 shows resultant curve and the linear fit used to determine the damping decrement.

Table 4.3 lists the natural damped frequency and damping factor for **Radius**. The frequency of the unloaded **Radius** arm is within 2% of the frequency measured for the lightly-loaded SRMS. The damping viscous-equivalent damping coefficient for **Radius**, however, was determined to be a factor of five larger than was measured for the SRMS. This difference is unlikely to be an issue because the damping in both mechanisms is very small.
This testing and measurement demonstrated that Radius is an appropriate system upon which to ground test the vision-assisted closed-loop control of a structurally flexible manipulator like the SRMS.

4.5 Follow-up Experimentation

The validation of the Operational SVS (OSVS) on orbit has been underway since the flight of STS-74 (November 1995). Verification of the OSVS will eventually need to include dynamical considerations; in fact, the International Space Station version of the vision system will be used to derive
CHAPTER 4. FLIGHT DATA ANALYSES

The dynamical behavior of the Space Station Remote Manipulator System (SSRMS).

The UTIAS Space Robotics group has been asked to consider what new (or supplemental) on-orbit testing would be appropriate based on the current data reduction and experimentation. The following tests may be a suitable starting point for the design of future on-orbit experiments.

It would be informative to see some comparative tests of the SRMS to allow for a more complete characterization of the manipulator's vibrational

Figure 4.18: Logarithmic Decrement of Radius Impulse Response
behavior. Three identical trajectories should be performed, but each would be executed with the arm in one of three separate modes, as follows:

1. In the first mode, the arm moves through a trajectory in single joint mode. In this mode, the arm is compliant; all joints are free to move, but only one joint is given a ramped current input. At the end of the trajectory, the brakes are manually switched on.

2. In the second mode, the arm performs the same trajectory in direct mode. In direct mode, the joints have the lowest compliance since all joints have brakes activated. All the joints have brakes on, and only the driven joint is given a command to release brakes as it receives a constant current (step function) input.

3. In the third mode, the arm again performs the same trajectory. However, in this case, the trajectory is carefully tailored as an autosequence in the orbiter rotation axis system (ORAS). In this mode, which is essentially equivalent to the manually augmented modes, all the joints have brakes off, but all joints are receiving ramped current inputs from the control software to maintain the trajectory.

With these tests, the arm behavior becomes more defined by repeatedly observing an identical end-effector trajectory under different arm conditions. In particular, the effects of joint compliance in vacuum/freefall can be quantified and compared with the test results of the SRMS in the ground testing on the precision air bearing floor. In addition, a comparison can be made between ramp and step current joint inputs.

These tests, ideally, would be run in such a manner that differences between the trajectories would be minimized. If possible, the trajectories should take place in the vicinity of the cargo bay so that the camera view includes some structure for verification of camera aim. In all the tests, the orbiter digital autopilot would be put into FREE mode to ensure an inertial reference frame for the experiments. The tailored autosequence trajectory must also be designed so that it is far from a singularity point; since the trajectory will be mimicking a single joint trajectory, the other joints should be driven as little as possible.
Another worthwhile test would be a repetition of the SVS-9 experiment, but with a larger mass. Data from this test would give an additional dataset with which to determine SRMS damping and stiffness factors. If possible, it would be particularly appropriate to repeat the trajectory #2 above with a different mass, so that the test conditions could be more closely correlated.
Chapter 5

Physical Testbed

5.1 Manipulator System

It was important to ensure that the vision system was provided with views for analysis which were representative of real views of a dynamic environment. For this study, representative views of target motion were produced in two ways: via targets attached to a flexible manipulator testbed and via targets attached to a stiffened and instrumented base.

5.1.1 Flexible Manipulator

The existence of the *Radius* flexible manipulator testbed at UTIAS facilitated and, to some degree, motivated this study. *Radius* provided a suitable testbed that required modifications of communications, cameras, lighting, and targeting. It did not, however, require any modification of controller boards, actuators or structure to incorporate machine vision. Figure 5.1 shows the testbed with targets added for vision feedback. The design parameters for the implemented target are discussed later in this chapter.

The Space Robotics Group at the University of Toronto Institute for Aerospace Studies established the *Radius* facility in response to the need for an ex-
experimental testbed for the validation of dynamics models and control methods for structurally flexible multilink bodies. As such, *Radius* provides a suitable environment for designing controllers for multilink manipulators with a high degree of flexibility. The baseline configuration for *Radius* is a two-link planar manipulator with rotary joints supported by airjets. The design is modular, with different linkages available to alter the behavior of the arm. Moreover, *Radius* can be configured to behave dynamically like
a two-dimensional version of SRMS. **Radius** exhibits geometric similarity to the SRMS and, as a result, has frequency and mode shape similarity. The manipulator speeds commonly used in **Radius** experimentation cause difficulties in tracking for the ASVS; visual servoing experiments will be conducted with lower manipulator speeds to reduce the target image velocity in the camera image. **Radius** normally operates at joints speeds well in excess of those permitted on-orbit, however, so differences in joint friction will have larger influence on the dynamic similarity of the two manipulators.

The **Radius** control computer is a Transtech system employing 8 T800 transputers and 4 T805 transputers. These transputer components are standard VME transputer boards and are unmodified. The analog output board is also a standard board but the analog input board has been modified for use with the **Radius** facility.

### 5.1.2 Target Manipulator

A stiffened base was instrumented with a target array mounted on a potentiometer. This device was designed to provide timing data upon which to evaluate the ASVS system latency. Figure 5.2 shows the circuit used to provide this potentiometer data to the ASVS for analysis. This target manipulator provided electrical feedback of the target motion with which a correlation with the motion (as measured visually) could be determined. By triggering the sample collection with the potentiometer output, simultaneous measurements could be made from the potentiometer and the photogrammetry output using the two available channels.

### 5.2 Photogrammetric Machine Vision Platform

The requirements placed on the photogrammetric platform were full camera frame rate and an object-space (as opposed to image-space) precision of $\pm 0.10$ inches and $\pm 0.10^\circ$. The only platform available which meets these criteria is the ASVS. In fact, it was the capabilities of the ASVS which first
prompted a study of machine vision for control of a low-frequency dynamic system.

The ASVS is comprised of a Intel 30486-based IBM-compatible personal computer with additional video processing boards. The 80486 motherboard is referred to as the Photogrammetry Processing Unit (PPU) in this application. The two video processing boards are the Video I/O Card and the Video Processing Card; each card utilizes two TMS320C40 digital signal processors. The ASVS software runs under the QNX 3.15F real-time operating system which provides fast context switching, multi-tasking, and priority-driven pre-emptive scheduling.

It is beyond the scope of this report to discuss the functionality of the QNX real-time operating system under which ASVS runs. The QNX 4.0 System Architecture manual [QNX Software Systems, 1993] has a thorough discussion of QNX microkernel and message passing that provides the basis for its real-time operation.
5.3 Camera Positioning

Figure 5.3: Camera Position with respect to Workspace.

Certain vision systems mandate the location of the camera with respect to the workspace. ASVS has no constraints in this regard; virtually any camera location can be made to work. It is not uncommon to mount a camera on the end-effector of a manipulator so that the camera moves with the manipulator as it negotiates the workspace. This would be a feasible way to integrate a camera on the *Radius* testbed. However, *Radius* has been constructed to provide certain levels of stiffness, damping and mass. The placement of a
camera system at the end-effector would require power and video cabling to be run along the lower and upper segments of the manipulator as well as the addition of over a kilogram for the camera itself. Operationally, such a camera would be exposed to higher incidences of impact should the manipulator overshoot its trajectory.

A decision was made to position the camera in a fixed location over the shoulder joint of *Radius*. This positions the camera over a point of zero translation on the manipulator and provides a suitable view of the manipulator workspace. The camera assembly was actually mounted at ceiling height to allow a standard focal length camera lens to provide a functional field of view. Figure 5.3 shows the relationship between the vision system camera and the manipulator workspace.

### 5.4 Camera Selection

The effects which can produce major inaccuracies in a video system have been discussed extensively in the literature [Wittels et al., 1988]. These effects include:

- anisotropic illumination (specular reflections and shadows)
- distortion in optical and video imaging (lens and photosensor irregularities)
- sensor image spatial quantization (Modulation Transfer Function)
- video signal bandwidth (low-pass luminance filtering)
- video signal sampling and quantization (digitization effects)
- signal to noise ratio

The input sensor is often the limiting component in any measurement system. This is the case for machine vision systems; the camera proves to be the weakest link. In the majority of vision systems, cameras prove difficult to
use in unstable lighting. Blooming, smearing and underexposure are frequent sources of machine vision failure. Because of processor constraints, however, many vision systems throw away an enormous amount of image data in order to provide solutions in real-time; hence, resolution is not important for many types of pattern recognition and single-task vision systems. Photogrammetry based on image-feature centroid determination, however, does rely on basic transducer resolution. In the case of ASVS, the full resolution is used within the tracking windows and the remainder of the image is not analyzed.

A number of different solid state cameras are available. Charge Injection Device (CID), multiplexed photosensor and Charge Coupled Device (CCD) technologies are all viable and available; CCD technology has benefitted from a broad consumer and commercial base and has good quality-to-cost ratios. CCD technology is rugged and reliable and has been developed sufficiently that good quality imaging can be performed over a reasonable range of lighting conditions.

The design, specification and testing procedures are structured to give images that look “good” to a human observer. In many cases, these images are not the optimal for machine vision. As an example, the resolution and gamma function (the illuminance transfer function) of a camera is often obscured by the K factor (aliased resolution) and contrast gains of the monitor on which an image is being viewed. Machine vision, on the other hand, receives and processes the camera output directly.

The ideal camera has a video output which has a one-to-one correlation with the scene illuminances at corresponding points in the scene. Any degradation in this correlation can be considered to be a camera defect. The ASVS/Radius application, in particular, places requirements on the camera to maximize the signal-to-noise ratio (SNR) by placing the highest significant scene illuminances just below the saturation level of the camera. This is done by matching the scene contrast to the video transfer function of the camera and also by using sampling processors and algorithms which optimally deal with the sampling noise.

The transfer function of output level versus sensor illuminance must usually be measured in preparation for a machine vision application. Nonlinear behavior such as blooming or smearing (intrusion of over-saturation signals into surrounding image areas) and graylevel shifting (changes in the transfer
function due to variation in average scene illuminance) need to be characterized. A camera transfer function is a curve of output voltage versus sensor illuminance (assume pixels all have the same response). In fact, camera pixels have strong variations in response and this is a major source of camera noise. Dark level and sensitivity also vary from pixel to pixel; sensitivity can even vary across the surface of one pixel. Cross-talk can occur between pixels by light and/or charge diffusion or via inefficient charge transfer during register-shifting or read-out. For the purposes of this study, the camera specifications were verified against a commercial RCA contrast chart with camera gamma (linearity) set to 1.0; this allowed verification of the camera specifications with regard to representative illuminances. Actual operation of the camera utilized a gamma setting of $\gamma = 0.45$ which invalidates the derived illuminance to output transfer function, but gives improved target contrast for the ASVS to analyze. Because of the extremely structured scene in the ASVS/\textit{Radius} study, this poses no difficulties.

The major theoretical tool for describing an optical system's resolution is the Modulation Transfer Function (MTF) which is a measure of the spatial frequency response of the camera normalized (usually) equal to one at low spatial frequencies. The response, in this regard, is the ratio of the contrast in the camera output to the contrast in the image. Obviously the MTF will decrease at high spatial frequencies because the pixels average and because the pixel output is sampled. Since we are interested only in a sampled centroid photocoordinates, we are mostly concerned with average spatial impulse response and are less concerned with locating insensitive regions between and inside pixels. We are, however, interested in a strongly uniform image; this required level of uniformity is commonly available even in consumer-grade CCD cameras.

Based on these requirements, a laboratory-grade grayscale CCD camera was selected for use in this study. A Cohu 4900 series camera was selected because it met all the requirements discussed above. In addition, the choice of the Cohu camera does not preclude multiple camera photogrammetry in future studies because it synchronizes with the leading edge of the video synchronization signal as does the ASVS. Additional Cohu cameras can therefore be added without synchronization discrepancies in the multi-camera photosolutions. Appendix B gives the manufacturer's specifications for the camera.
5.5 Target Array Design

ASVS is capable of tracking corners, lines, ends of lines, and the centroid of an arbitrary feature. Furthermore, ASVS digitizes an image into 256 grayscale levels to provide data for its binary thresholds. It would seem straightforward, then, to aim the camera at Radius and choose some natural features to track. This would lead, unfortunately, to experimental conditions which are far from optimal. A discussion of these conditions will clarify this statement.

The complexity of the current imaging process is routinely underestimated or oversimplified in machine vision research. In pursuing viable machine vision solutions, it is essential to understand how a video camera constructs an image of a scene. A thorough understanding enables researchers to provide features which will improve the capability of the machine vision process in handling the image. In the following subsections, an analysis is conducted to determine a suitable set of arrays for the Radius testbed implementation based on the process by which a camera produces an image of a target.

5.5.1 Centroid Determination

The manner in which ASVS determines a target image centroid determines how a target array should be configured for a strong photosolution (i.e., an unambiguous pattern which is sufficiently sensitive to changes in object-space attitude). The following subsections discuss this centroid determination process and outlines the target array design process.

Video Line Signals

This discussion will begin with the video signal of a feature at the video line level. Color information exists as a high frequency signal added to the basic intensity signal. This is an artifact of the requirement that color television (National Television Standards Committee or NTSC) needed to be backward compatible with the original 525/60 black and white (CCIR-M) standard. If color is not used in the image processing, it can be removed using a low-pass
filter without loss of signal intensity. This discussion will assume that only the intensity information is available and that it is the only information of interest.

Figure 5.4: Video signal (one line) of a centered dark feature.

Figure 5.4 shows the signal produced by a dark feature for one video line. The voltage drop is dependent on the difference in the intensity of the incident light from the feature and from the background. This intensity difference results from a difference in scene reflectance between the light source and the camera. The voltage difference, however, is also dependent upon the automatic gain control (AGC) and gamma functions of the camera. The AGC sets the average graylevel of the scene so that the camera will adapt automatically to changing lighting conditions and low light conditions. The gamma function produces more contrast difference in brighter objects by
compressing the contrast difference in darker objects (logarithmic intensity response as opposed to linear response). Figures 5.5(a) and 5.5(b) show the same feature signature with AGC enabled, and gamma of 0.45 enabled respectively.

Figure 5.5: Video signal of feature with a) AGC enabled and b) $\gamma = 0.45$ enabled.

Figure 5.6 shows the feature when partially distorted by a specular reflection. Note that there is a distortion of the feature centroid and saturation of the camera sensor; these camera effects cause dramatic problems for an analytic machine vision system.

Tracking Window Level

The tracking windows are subsets of the entire image. A tracking window is comprised by (on the order of) 10 video lines by 10 pixels. The on-line processor is only concerned with the contrast pattern within a tracking window. Within the tracking window, ASVS calculates a binary threshold to separate feature from background, determines the area of the feature and calculates the moment of the feature with respect to the image coordinate frame. The area is used for automatically sizing the tracking window and the moment is used for both the photosolution and for the tracking filter (to move the tracking window within the image). Note that any feature can be tracked in this manner. The optimal feature shape is determined by another fac-
Figure 5.6: Video signal of a dark feature distorted by a specular reflection.

Anti-Aliasing of Features

A CCD camera generates a discretized image of pixels and lines. Geometric shapes with flat edges which are imaged in this manner can exhibit a high degree of aliasing. Figure 5.7 shows a square shape and the pixels it activates in an image before and after it is moved $\frac{5}{12}$ pixel. Note that the same pixels are activated in both cases despite the change of position.
The fewer sides a geometric shape has, the more prone it is (on average) to spatial aliasing. Increasing the number of sides on a geometric shape yields a circle (or dot) in the limit as the number of sides approaches infinity. Thus, a dot has the highest resistance to imaging aliasing (Figure 5.8). In the case of a dot, a movement of only $\frac{2}{12}$ of a pixel causes a different region of pixels to be activated.

**CCD Effects**

A CCD images a bright feature by building up a charge on pixels illuminated by the real image of that bright feature. This charge will tend to “spill” into adjacent pixels; this spillage tends to make bright features larger. Dark features, on the other hand, tend to shrink (lose pixels) from the spillage from the bright surroundings. Figure 5.9 shows how a dark feature and a bright feature of the same size appear in CCD generated video. Since the ASVS samples the pixels in a feature to determine its centroid, it is preferable to have bright targets on a dark background to take advantage of the additional pixels activated by the bright feature.
CHAPTER 5. PHYSICAL TESTBED

Grouped Features

The arrangement of target features in a target array has two principal guidelines. First, the distances between coplanar target features in an image should be as large as is practical. Second, a target feature which is out of plane of the principal planar array will provide substantially improved pitch and yaw measurements; the pitch and yaw photosolutions are coupled mathematically to the range photosolution. By providing a better pitch/yaw cue in the target array, ambiguities are resolved in three of the six degrees of freedom resulting in an improved photosolution in all degrees of freedom.

Figure 5.8: Aliasing Behavior of a Circular Object
5.5.2 Planar Manipulator Target Final Design

The first version of a target array suitable for Radius has been designed. Figure 5.10 shows the approximate geometry of the array. The following list shows the parameters used in the target design as explained in the previous section:

1. Camera fixed in oblique location over the Radius shoulder joint
2. Camera lens: manual iris 16 mm. focal length lens (no IR filter)
3. Target dot diameter: 8 pixels in image plane
4. Target dot size vs. background size ratio: 1:4
5. Image VFOV: 480 pixels corresponds to 2.0 meters in object space
6. Target dots/Target Background: White on Black
These parameters resulted in a target array which is defined as follows:

1. Combination of a quadrilateral and two peg-type arrays using five targets. Peg height is 8.25 centimeters and the quadrilateral geometry is 17.25 centimeters on a side.
2. Target dot size is 3.6 centimeters (diameter).
3. Target background size is 15 centimeters (diameter).

Figure 5.10: *Radius* Vision Target Geometry.

### 5.6 Lighting

The Spacecraft Dynamics and Space Robotics Laboratory has a high degree of light noise. The Lab is lighted with 80 fluorescent tubes which produces
an even and relatively shadowless scene. However, the light produced by the unshielded bulbs is quite intense and, in combination with the particular configuration of the *Radius* table, produces strong specular reflections from the acrylic air-bearing surface. A decision was therefore made to use a separate lighting source for the experimental testbed. Collocated light sources work well with CCD television cameras; in fact, most remote-use media cameras use a built-in lighting source. When retroreflective targets are used, it becomes essential to collocate a source and to balance the light source around the sensor.

### 5.6.1 Wattage

A conventional 0%-100% Variac was used to vary power to the collocated light source. Initially, two 40-watt household-grade diffuse lightbulbs were installed with the intention to upgrade to two 50-watt spotlights. The 40-watt bulbs were found to provide sufficient illumination for the retroreflective targets.

### 5.6.2 Thermal

An aluminum framework (Figure 5.11) was built to position the light sources equidistant from the camera lens and to direct the light in the same direction at the camera optic axis. The framework also served to aim the camera and hold light sources at a sufficient distance to avoid thermal damage to the camera itself.

### 5.7 Connectivity

The ASVS has been incorporated as the main component of the vision servoing loop of the *Radius* testbed via a serial connection (Figure 5.12). Effectively, ASVS behaves like a laboratory instrument providing position and rotation information. Internally, ASVS performs a number of tasks required to provide a robust photogrammetric solution. Five separate processors are
used for: video input processing, video processing, image processing, photogrammetry and video output processing. Eight command pathways connect these processors and the real-time code is responsible for ensuring that each process is completed within its task time.

Figure 5.13 shows the process flow of the data through the single-camera task schedule. It was vital that this task flow not be interrupted by the load placed on the ASVS when integrated into the Radius testbed.
5.8 Measurement Transformations

Following extraction of the requisite photogrammetric data for a given frame, the data requires an additional transformation to convert the measurement from yaw-pitch-roll camera coordinates into pitch-yaw-roll manipulator coordinates. This transformation is accomplished by using the vectors derived with the camera aim (AIM) and target deformation (TAP) calibrations run in real-time on the ASVS.

The measurement produced by the ASVS and accessed for this experiment is the raw vector produced by the photosolution process. This is the pose...
CHAPTER 5. PHYSICAL TESTBED

Figure 5.13: Modification in ASVS Task Flow for Incorporation of *Radius*-required Data.
measurement of the target array with respect to the camera optical center coordinate system.

**Reference Frames.** For simplicity at this stage of development, in which the vision system is of greatest concern, it is useful to consider only the pose of the end-effector and not the relative rotations of rest of the manipulator. Denote by $\mathcal{F}_P$ (payload) the reference frame fixed to the end-effector.

Similarly denote:

- $\mathcal{F}_T$ = reference frame of the target array
- $\mathcal{F}_C$ = reference frame of the camera optical center
- $\mathcal{F}_H$ = reference frame of the camera housing
- $\mathcal{F}_A$ = reference frame of the camera aiming system
- $\mathcal{F}_G$ = reference frame of the general frame
- $\mathcal{F}_B$ = reference frame of the berthing point

The $\mathcal{F}_T$, $\mathcal{F}_C$, $\mathcal{F}_H$, and $\mathcal{F}_A$ all define the relationship between the camera aiming position and the target array being measured. The $\mathcal{F}_G$ (general) reference frame provides a useful global origin; for the *Radius* experiment its origin coincides with that of the shoulder joint of the manipulator. The $\mathcal{F}_B$ (berthing) reference frame corresponds to some nominal position if the payload frame; in this instance, the berthing frame origin coincides with the pose of the end-effector with zero joint and boom deflection.

The ASVS has calibration routines that allow for fine-tuning of the measured berthing position and of the camera aim angles and effective focal length. These routines correct for the intrinsic uncertainties in the real-world operating environment and allow the system to work more robustly in measuring relative and absolute distances in object space. These calibrations act as a metric; they result in the measured image space being superimposed upon the measured object space within the ASVS database. The three vectors which can be calibrated in this manner are: SCT, SBT, and SOB which correspond
to the transformations $\mathcal{F}_C$ to $\mathcal{F}_T$, $\mathcal{F}_B$ to $\mathcal{F}_T$, and $\mathcal{F}_O$ to $\mathcal{F}_B$ respectively. The physical meaning of these transformations is shown in figure 5.14.

Software modifications were made to the main photogrammetry loop to allow these calibrations to be accessed by the data output stream from the Radius-dedicated ASVS as shown in figure 5.13.

Figure 5.14: ASVS Calibrated Transformations
Chapter 6

Characterization

6.1 Camera Lens Calibrations

Mathematical modeling of a camera lens and sensor chip is not feasible in terms of accuracy and processing times. A more effective means to handle the effects of the imaging process on the image is to provide a *riseau* reference frame in object space that can be used to map into image space. In the case of the ASVS, a procedure is undertaken to position a machined target in precise alignment with the optical axis of the camera. The ASVS is then able to generate a 165 component look-up table that allows correction of the camera lens and scan irregularities. Iterations of this procedure permit the calculation of appropriate gain ratios for a given focal length as well as the effective focal length and optical center of the camera lens assembly.

The camera lens/scan calibrations were performed at the NRCC laboratories in Ottawa to provide these look-up tables for the ASVS error correction routines. Calibrations were performed on three camera lenses at two different iris and gamma settings. The procedures used are quite detailed and are documented completely in a recently updated Neptec internal document [Parent, 1995].
6.2 Measurement Latency

Perhaps the most important parameter in a transducer is latency. This test presented the greatest difficulties because of the simultaneous measurements of a mechanical parameter. The fundamental requirement of this identification test were to measure the time delay between object motion and ASVS output of that motion. In order to accomplish this, two independent measurements of a target position must be measured simultaneously and recorded for statistical comparison.

A number of difficulties arose during this characterization. The ASVS photoalgorithms (particularly the general algorithm) were unable to handle total relative target rotation (in camera roll) of greater than 180°. Communication from the ASVS to an external device, which was required for data synchronization, proved to be problematic. Smooth motion of test target array also posed experimental difficulties. These issues were resolved using the testbed apparatus described in Sections 5.1 and 5.2 and the procedures outlined in the following paragraphs.

In this case we have a dynamic measurand (a time delay which may vary with frame sampling) which is best measured by creating a steady-state condition and measuring repeatedly. As mentioned previously, the ASVS performs best when measuring motion in the plane of image; i.e., roll, X-axis or Y-axis motion with respect to the camera. Translational motion of a target array will, unfortunately, result in the target array leaving the field-of-view of the camera very quickly. This leaves target array roll motion as the best candidate for this characterization. In addition, mechanical rotation transducers (e.g. potentiometers) are cheaper, more reliable, and have a larger range of motion than linear displacement transducers.

The ASVS photoalgorithms currently have limitations on the total rotation that a given array definition can undergo. Because of this limitation, the testing was restricted to rotations of less than 180° of total motion. Instead of creating a steady-state condition and repeatedly measuring the time delay, a single pulse of rotational motion was given to the target array and the motions measured by the potentiometer and by the vision system were stored to a small file. This procedure was repeated numerous times to build up enough data to handle statistically. Figure 6.1 shows a plot of the potentiometer data.
(normalized in magnitude) versus the vision data for one of the maneuvers.

The quartz oscillators on most commercial CPUs have a high degree of accuracy and precision so the provability of the time measurement can be ensured by monitoring the performance of the system clock over a period of hours or days. The ASVS clock is checked on a regular basis and is in error by less than one second in 30 million.
6.2.1 Transducer Latency

This characterization measured the amount of time delay introduced into the visual servoing loop by the actions of the camera and ASVS in digitizing an image, converting it to an analog signal for transmission, redigitizing, extracting photocoordinates, performing a photogrammetry algorithm and producing a result. Table 6.1 shows the results of 22 sets of tests:

Table 6.1: Transducer (ASVS) Latency (in milliseconds)

<table>
<thead>
<tr>
<th></th>
<th>No. samples</th>
<th>Mean</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Set</td>
<td>10</td>
<td>83.65</td>
<td>19.49</td>
</tr>
<tr>
<td>Combined Set</td>
<td>220</td>
<td>76.11</td>
<td>21.27</td>
</tr>
</tbody>
</table>

Figure C.1 shows the probability distribution for the combined test data sets. The large standard deviation is due to the size of a frame (52 ms) relative to the size of the measurand.

6.2.2 Communication Delay

This characterization provides measurements for the servo loop delay produced by both the transducer and the time required to communicate the data to the control computer. Table 6.2 shows the results of the testing:

The probability distribution is essentially the same as for the transducer delay given above. The communications add additional latency into the servo loop, but do not contribute greatly to the uncertainty in the delay.
6.3 Sampling Rate

The sampling rate of a measurement system is crucial to the construction of a viable controller. The update rate of the ASVS was tested rigorously to ensure that it was producing repeatable and consistent sampling rates. Again, the clock on the ASVS motherboard was used to time the interval between photogrammetry calculations. In this instance, however, the time measurements were much shorter and no external equipment was required.

A module was inserted in the photosolution task to copy the system time in milliseconds to an open file stream. Only three significant digits were saved since the available system clock resolution is 1.0 milliseconds and the expected sampling rate was 50 milliseconds for the developmental ASVS platform being tested. This testing was undertaken with an understanding that measurand and the comparator were of similar magnitude. That is, measurements were to be on the order of 50 milliseconds measured against a standard clock cycle of one millisecond.

Table 6.2: Transducer and Communications Latency (in milliseconds)

<table>
<thead>
<tr>
<th></th>
<th>No. samples</th>
<th>Mean</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Set</td>
<td>10</td>
<td>90.45</td>
<td>26.02</td>
</tr>
<tr>
<td>Combined Set</td>
<td>220</td>
<td>84.07</td>
<td>21.4</td>
</tr>
</tbody>
</table>

Table 6.3: Vision System Sampling Rate Measurement (in milliseconds)

<table>
<thead>
<tr>
<th></th>
<th>No. samples</th>
<th>Mean</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Set</td>
<td>100</td>
<td>52.01</td>
<td>0.10</td>
</tr>
<tr>
<td>Combined Set</td>
<td>10000</td>
<td>52.00</td>
<td>0.01</td>
</tr>
</tbody>
</table>
The sampling frequency appeared to be completely stable. There was no evidence of the rate drifting over long periods of operation. Long duration testing had to be conducted since the measurement resolution was only 1.0 milliseconds. Table 6.3 shows the results of the sampling rate testing. (The mean value of the sample test set is shown to greater than three significant digits for comparative purposes.) The measured sampling rate was 52 milliseconds which corresponds to a sampling frequency of 19.23 Hz. This sampling frequency is a function of the prototype ASVS unit currently in use; the flight-equivalent unit has its sampling rate controlled by the camera frame rate of 30 Hz.

This measurement was also checked against an oscilloscope reading of the serial port output produced by the ASVS for the Radius control computer. Identical behavior was observed which supports the previous findings and increases confidence in the robustness of communications from the ASVS unit.

6.4 Precision

Tests were conducted to ensure that ASVS was giving sufficient fidelity of measurement. Tests of this nature test all aspects of the ASVS built-in calibration routines as well as the applicability of the camera lens calibration to the focal range of the camera/lens assembly. Primarily, however, the test was conducted to determine the repeatability of the position measurement for camera distances and conditions similar to those of the dynamics experiment.

In this case, the precision of the vision system (a static measurand) was measured against the precision of a micrometer. Under ideal circumstances, an encoded optical track would be used to ensure the best possible position measurement for comparison with the vision measurement. For this test a digital micrometer (Fowler and NSK Max-Cal) was used to measure changes in target location; the micrometer can resolve down to \( \frac{5}{10000} \) inches which is an order of magnitude better than the theoretical limits of the vision system. The limit on the comparative measurement was actually the capacity of the experimenter to measure the change in target position with a micrometer.
Forty-three target positions were measured from deviation from a calibrated point. Each of these positions were sampled 60 times using the vision system to produce 2580 measurements. A systematic error was found in three of the test sets; this bias error was attributable to inaccurate micrometer measurements on the part of the experimenter and the three affected sets were discarded.

Table 6.4: Repeatability of Vision System Position Measurements (in inches)

<table>
<thead>
<tr>
<th></th>
<th>No. samples</th>
<th>Mean</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Set</td>
<td>60</td>
<td>-0.0837</td>
<td>0.4597</td>
</tr>
<tr>
<td>Combined Set</td>
<td>2400</td>
<td>-0.0319</td>
<td>0.4142</td>
</tr>
</tbody>
</table>

Table 6.4 show the results of the measurement precision testing assuming zero-error micrometer measurements by the experimenter. If a reasonable assumption is made that the micrometer readings are accurate to within $\frac{5}{100}$ of an inch, a reasonable expectation of uncertainties to within $\frac{1}{10}$ of an inch can be shown. Figure C.2 shows the probability distribution for the combined test data sets.
Chapter 7

Conclusion

This work has been done with a presupposition that it provide a framework for continued research towards visual servoing of a flexible manipulator. It is useful to make an accounting of issues and shortcomings of the current status of this framework and to set forth some recommendations regarding task that need to be completed in order to achieve this goal.

7.1 Issues to be Resolved

A number of shortcomings have been identified within the testbed with regards to the visual feedback loop. These shortcomings arise from the software and hardware configuration of the ASVS vision system; the remedies for these deficiencies are dependent on the specific cause.

One of the problems that has been plaguing operations with the ground testbed is the loss of photosolution with target rotations (roll) in excess of $\pm 45^\circ$ with respect to the camera. The reason for this failure stems from the algorithm used to determine the photosolution from an arbitrary arrangement of target elements. The algorithm that handles these situations is known as the General Algorithm. This problem is particularly troublesome because it occurs silently; the software simply presents $\pm 45^\circ$ as the
photosolution and does not announce that there is an error. Currently, the workaround for this problem is to avoid target orientations that result in this unannounced error or to use a lower-order solution based on a photogrammetry algorithm which has been tailored to a symmetric target array.

The current hardware configuration of the ASVS-Traquair unit results in relatively poor intensity thresholding (and therefore target element tracking). This issue arises as a result of using commercially available video processing boards to emulate the real-time ASVS hardware; this issue does not exist for the ASVS units that contain the custom hardware. The current workaround for this problem is to control the ambient lighting carefully and direct illumination to the vision system target array. Installation of the upgraded ASVS hardware will alleviate the requirements for strict illumination control and improve the robustness of the ASVS operation.

Similarly, the sampling rate and frame synchronization of the current ASVS-Traquair unit is substandard. There is no way to handle this problem since the data stream leaves the ASVS at 20 Hz and is only loosely clocked to the camera synchronization signal. Again, an upgrade to flight-equivalent hardware will rectify this situation.

### 7.2 Future work

The proposed follow-up research should:

- Develop complimentary software simulation which will allow more rapid prototyping of control algorithms.
- Develop vision control algorithms specifically applicable to space manipulator systems such SRMS and SSRMS;
- Develop vision control algorithms applicable to general robotic manipulator systems in that all large manipulators exhibit flexibility in the links and joints;
- Develop the theory of artificial neural networks in the area of machine vision; and
• Extend the applicability of the ASVS by demonstrating its effectiveness with vision-in-the-loop control.

While the modified *Radius* testbed now provides a good experimental apparatus for studying visual servoing, it is far more efficient to explore control algorithms in simulation. Computer simulation permits the gains of a controller to be varied easily and allows for algorithm testing to proceed with well-understood uncertainties. The capability of controlling all of the relevant state variables, control inputs, exogenous inputs and disturbances will allow a controller designer to understand fully the inherent strengths and weaknesses of a given control scheme. The same flexibility is not obtainable using hardware.

Control algorithm design shall occur in three stages: (1) the use of vision with the current implementation of the MEETT control techniques to calibrate zero points for the strain sensors, (2) the use of vision to provide the strain sensing to the MEETT algorithm in a vision-assisted servoing scheme, and finally (3) the use of vision to provide bandwidth-reduced data to a neural-network visual servoing controller. The aim here is to attempt to extend understanding of vision-related effects from controllers that have already been shown to be effective. Ultimately, the goal is to survey the spectrum of control philosophies from optimal to neural-based.

This neural-based/statistical approach to robotic control does not, however, make completely obsolete model-based control. Indeed, one can imagine that an "optimal" position exists on the control spectrum somewhere between traditional model-based control and the *avant garde* non-model-based control as exemplified by the neural-network concept.

To this end, it will be another effort to develop hybrid techniques which seek to utilize the best of both concepts. For example, the end-effector trajectory controller discussed above has been augmented [Carusone, 1998] with a neural-network controller, using reinforcement learning, to "tune" the feedback gains in accordance with a prescribed performance index. This hybrid system is able to eliminate almost completely the time delay caused by the nonminimum-phase character of flexible manipulators.
7.3 Synopsis

The overall objective of this thesis was to establish the feasibility of collecting sufficient visual information to pursue vision-assisted servoing of a flexible manipulator and, if practical, to establish a means by which this visual information can be supplied to the manipulator control system with sufficient robustness, timeliness, and fidelity. These objectives have been met.

The groundwork has been set to pursue a study of vision-assisted servoing (and visual servoing) of a robotic manipulator with structural flexibility. The three main tasks required to lay this groundwork were:

**Feasibility.** An analysis of on-orbit data indicates that it is reasonable to use visual information to provide dynamic structural data from a flexible manipulator in real-time. Specifically, dynamic photogrammetric data from Space Shuttle Mission STS-52 was analyzed to identify certain structural parameters of a lightly loaded SRMS manipulator arm. It was determined that realistic natural frequencies of large flexible space manipulators have their first few harmonic frequencies within the Nyquist frequency of video camera sampling rates. Furthermore, the data produced by the system has adequate precision and robustness to encourage further study.

**Testbed Modifications.** An existing ground-based testbed has been modified to permit testing of end-effector control algorithms based upon vision feedback. A high-performance vision system has been modified and installed in an existing flexible manipulator apparatus. In particular, the ASVS machine vision system has been integrated into the *Radius* facility at the University of Toronto Institute for Aerospace Studies. Target and lighting systems have been designed, tested and incorporated to provide support for the vision system function.

**System Characterization.** This testbed has been characterized for parameters required in the control algorithm development. Identification of system parameters was performed for all communication pathways to determine data transfer latencies and for transducer performance and sampling
rate. Particular emphasis was placed on the latencies incurred by the photogrammetry and photosolution algorithms and on the time delays produced by data transmission from the ASVS unit.

Controllers in which vision sensors are utilized (whether alone or in combination with other technologies) promise to provide the most robust and adaptable means of controlling autonomous robotics in teleoperational and/or unstructured environments. The fully characterized testbed now provides a framework within which vision-assisted and visual servoing can be explored. Shortcomings in the current testbed configuration have been identified either as experimental constraints or as items to be remedied. The testbed now fulfills the role of a functional and well understood tool for the study of vision-based control.
References


### Appendix A

#### Abbreviations and Acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGC</td>
<td>Automatic Gain Control</td>
</tr>
<tr>
<td>ASAD</td>
<td>All Singing, All Dancing</td>
</tr>
<tr>
<td>ASVS</td>
<td>Advanced Space Vision System</td>
</tr>
<tr>
<td>DTO</td>
<td>Detailed Test Objective</td>
</tr>
<tr>
<td>CAP</td>
<td>Canadian Astronaut Program</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge-Coupled Device</td>
</tr>
<tr>
<td>CID</td>
<td>Charge Injection Device</td>
</tr>
<tr>
<td>CSA</td>
<td>Canadian Space Agency</td>
</tr>
<tr>
<td>CTA</td>
<td>Canadian Target Assembly</td>
</tr>
<tr>
<td>GPC</td>
<td>General Purpose Computer</td>
</tr>
<tr>
<td>IAMT</td>
<td>Institute for Advanced Manufacturing Technologies</td>
</tr>
<tr>
<td>LEO</td>
<td>Low Earth Orbit</td>
</tr>
<tr>
<td>LDB</td>
<td>Launch Data Bus</td>
</tr>
<tr>
<td>MCIU</td>
<td>Manipulator Control Interface Unit</td>
</tr>
<tr>
<td>MDF</td>
<td>Manipulator Development Facility</td>
</tr>
<tr>
<td>MEETT</td>
<td>Manipulator End-Effector Trajectory Tracking</td>
</tr>
<tr>
<td>MTF</td>
<td>Modulation Transfer Function</td>
</tr>
<tr>
<td>NRCC</td>
<td>National Research Council of Canada</td>
</tr>
<tr>
<td>NSERC</td>
<td>National Sciences and Engineering Research Council</td>
</tr>
<tr>
<td>NTSC</td>
<td>National Television Standards Council</td>
</tr>
<tr>
<td>OBAS</td>
<td>Orbiter Body Axis System</td>
</tr>
<tr>
<td>OI</td>
<td>Operational Instrumentation</td>
</tr>
</tbody>
</table>
APPENDIX A. ABBREVIATIONS AND ACRONYMS

OMS  Orbiter Maneuvering System
OMV  Orbital Maneuvering Vehicle
ORAS Orbiter Rotation Axis System
PCMMU Pulse Code Master Measurement Unit
PDRS Payload Deployment and Retrieval System
POR Point of Resolution
PPU Photogrammetry Processing Unit
RCU Remote Control Unit
RCS Reaction Control System
SES Systems Engineering Simulator
SNR Signal to Noise Ratio
SOP SVS Vector - Orbiter to Payload
SRMS Shuttle Remote Manipulator System
SSRS Space Station Remote Manipulator System
STS Space Transportation System
SVS Space Vision System
SVS-1 System Check and Calibration
SVS-2 Grapple / Servicing Task
SVS-3 Berthing Assembly Task
SVS-4 Characterization Test
SVS-5 Guidance Maneuvers
SVS-6 Short-Range Proximity Operations
SVS-7 CTA Deploy, Stationkeeping, DTO
SVS-8 CTA Re-capture (deleted)
SVS-9 SRMS Structural Deflections
TAP Target Array to Payload (calibration)
TFL Telemetry Format Load
UTIAS University of Toronto - Institute for Aerospace Studies
VSU Video Switching Unit
Appendix B

Complete On-orbit Results

B.1 SRMS Position #1

B.1.1 Maneuver 1.1

Table B.1: Fundamental Natural Frequencies and Viscous Equivalent Damping Decrement (δ) for SRMS Reference Position #1 (Maneuver 1)

<table>
<thead>
<tr>
<th></th>
<th>X-Axis</th>
<th>Y-Axis</th>
<th>Z-Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>0.237</td>
<td>0.237</td>
<td>0.237</td>
</tr>
<tr>
<td>Frequency (rad/s)</td>
<td>1.49</td>
<td>1.49</td>
<td>1.49</td>
</tr>
<tr>
<td>Damping Decrement, δ</td>
<td>-0.029</td>
<td>-0.022</td>
<td>-0.008</td>
</tr>
</tbody>
</table>
Figure B.1: SVS-9 Maneuver 1-1 (3 Axes) with Roll 19.48 and Yaw 8.4
Figure B.2: SVS-9 Maneuver 1-1 (X Axis) with Roll 19.48 and Yaw 8.4

Figure B.3: Logarithmic Decrement Plot - SVS-9 Maneuver 1-1 (X Axis)
Figure B.4: SVS-9 Maneuver 1-1 Power Spectral Density (X Axis)
B.1.2 Maneuver 1.2

Figure B.5: SVS-9 Maneuver 1-2 (3 Axes) with Roll 19.48 and Yaw 0
Figure B.6: SVS-9 Maneuver 1-2 (X Axis) with Roll 19.48 and Yaw 0

Figure B.7: Logarithmic Decrement Plot - SVS-9 Maneuver 1-2 (X Axis)
Table B.2: Fundamental Natural Frequencies and Viscous Equivalent Damping Decrement ($\delta$) for SRMS Reference Position #1 (Maneuver 2)

<table>
<thead>
<tr>
<th></th>
<th>X-Axis</th>
<th>Y-Axis</th>
<th>Z-Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>0.295</td>
<td>0.295</td>
<td>0.472</td>
</tr>
<tr>
<td>Frequency (rad/s)</td>
<td>1.85</td>
<td>1.85</td>
<td>2.97</td>
</tr>
<tr>
<td>Damping Decrement, $\delta$</td>
<td>-0.059</td>
<td>-0.079</td>
<td>-0.040</td>
</tr>
</tbody>
</table>

Figure B.8: SVS-9 Maneuver 1-2 Power Spectral Density (X Axis)

Note: The $Z$ component of the oscillation is very small compared with the $X$ component and occurs within the pitch plane of the manipulator.
B.1.3 Maneuver 1.3

Figure B.9: SVS-9 Maneuver 1-3 (3 Axes) with Roll 19.48 and Yaw 0
Figure B.10: SVS-9 Maneuver 1-3 (Y Axis) with Roll 19.48 and Yaw 0

Figure B.11: Logarithmic Decrement Plot - SVS-9 Maneuver 1-3 (Y Axis)
Figure B.12: SVS-9 Maneuver 1-3 (Z Axis) with Roll 19.48 and Yaw 0

Figure B.13: Logarithmic Decrement Plot - SVS-9 Maneuver 1-3 (Z Axis)
Figure B.14: SVS-9 Maneuver 1-3 Power Spectral Density (Y Axis)

Figure B.15: SVS-9 Maneuver 1-3 Power Spectral Density (Z Axis)
Table B.3: Fundamental Natural Frequencies and Viscous Equivalent Damping Decrement $\delta$ for SRMS Reference Position #1 (Maneuver 3)

<table>
<thead>
<tr>
<th></th>
<th>X-Axis</th>
<th>Y-Axis</th>
<th>Z-Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>0.218</td>
<td>0.218</td>
<td>0.218</td>
</tr>
<tr>
<td>Frequency (rad/s)</td>
<td>1.37</td>
<td>1.37</td>
<td>1.37</td>
</tr>
<tr>
<td>Damping Decrement, $\delta$</td>
<td>0.005</td>
<td>-0.015</td>
<td>-0.012</td>
</tr>
</tbody>
</table>

Note: The positive decrement in the $X$ component results from cross-coupled energy leaking from the large $Y$ and $Z$ components into the much smaller $X$ component.
B.1.4 Maneuver 1.4

Figure B.16: SVS-9 Maneuver 1-4 (3 Axes) with Roll 19.48 and Yaw 0
Figure B.17: SVS-9 Maneuver 1-4 (Y Axis) with Roll 19.48 and Yaw 0

Figure B.18: Logarithmic Decrement Plot - SVS-9 Maneuver 1-4 (Y Axis)
Figure B.19: SVS-9 Maneuver 1-4 (Z Axis) with Roll 19.48 and Yaw 0

Figure B.20: Logarithmic Decrement Plot - SVS-9 Maneuver 1-4 (Z Axis)
Figure B.21: SVS-9 Maneuver 1-4 Power Spectral Density (Y Axis)

Figure B.22: SVS-9 Maneuver 1-4 Power Spectral Density (Z Axis)
Table B.4: Fundamental Natural Frequencies and Viscous Equivalent Damping Decrements (\(\delta\)) for SRMS Reference Position #1 (Maneuver 4)

<table>
<thead>
<tr>
<th></th>
<th>X-Axis</th>
<th>Y-Axis</th>
<th>Z-Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>0.223</td>
<td>0.402</td>
<td>0.223</td>
</tr>
<tr>
<td>Frequency (rad/s)</td>
<td>1.40</td>
<td>2.53</td>
<td>1.40</td>
</tr>
<tr>
<td>Damping Decrement, (\delta)</td>
<td>-0.041</td>
<td>-0.025</td>
<td>-0.023</td>
</tr>
</tbody>
</table>

Note: The Y component of the oscillation has some energy in the second harmonic. This results in a frequency roughly double that of the Z component (the major component of the vibration in this instance).
B.2 SRMS Position #2

B.2.1 Maneuver 2.1

Figure B.23: SVS-9 Maneuver 2-1 (3 Axes) with Roll 19.48 and Yaw 8.3
Figure B.24: SVS-9 Maneuver 2-1 (X Axis) with Roll 19.48 and Yaw 8.3

Figure B.25: Logarithmic Decrement Plot - SVS-9 Maneuver 2-1 (X Axis)
Table B.5: Fundamental Natural Frequencies and Viscous Equivalent Damping Decrement $\delta$ for SRMS Reference Position #2 (Maneuver 1)

<table>
<thead>
<tr>
<th></th>
<th>X-Axis</th>
<th>Y-Axis</th>
<th>Z-Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>0.218</td>
<td>0.218</td>
<td>0.218</td>
</tr>
<tr>
<td>Frequency (rad/s)</td>
<td>1.37</td>
<td>1.37</td>
<td>1.37</td>
</tr>
<tr>
<td>Damping Decrement, $\delta$</td>
<td>-0.015</td>
<td>-0.017</td>
<td>-0.029</td>
</tr>
</tbody>
</table>

Figure B.26: SVS-9 Maneuver 2-1 Power Spectral Density (X Axis)
B.2.2 Maneuver 2.2

Figure B.27: SVS-9 Maneuver 2-2 (3 Axes) with Roll 19.48 and Yaw 0
Figure B.28: SVS-9 Maneuver 2-2 (X Axis) with Roll 19.48 and Yaw 0

Figure B.29: Logarithmic Decrement Plot - SVS-9 Maneuver 2-2 (X Axis)
Table B.6: Fundamental Natural Frequencies and Viscous Equivalent Damping Decrement ($\delta$) for SRMS Reference Position #2 (Maneuver 2)

<table>
<thead>
<tr>
<th></th>
<th>X-Axis</th>
<th>Y-Axis</th>
<th>Z-Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>0.228</td>
<td>0.228</td>
<td>0.228</td>
</tr>
<tr>
<td>Frequency (rad/s)</td>
<td>1.43</td>
<td>1.43</td>
<td>1.43</td>
</tr>
<tr>
<td>Damping Decrement, $\delta$</td>
<td>-0.012</td>
<td>-0.024</td>
<td>-0.020</td>
</tr>
</tbody>
</table>

Figure B.30: SVS-9 Maneuver 2-2 Power Spectral Density (X Axis)
B.2.3 Maneuver 2.3

Figure B.31: SVS-9 Maneuver 2-3 (3 Axes) with Roll 19.48 and Yaw 0.5
B.2.4 Maneuver 2.4

Figure B.32: SVS-9 Maneuver 2-4 (3 Axes) with Roll 19.48 and Yaw -1.875
Figure B.33: SVS-9 Maneuver 2-4 (Y Axis) with Roll 19.48 and Yaw -1.875

Figure B.34: Logarithmic Decrement Plot - SVS-9 Maneuver 2-4 (Y Axis)
Figure B.35: SVS-9 Maneuver 2-4 (Z Axis) with Roll 19.48 and Yaw -1.875

Figure B.36: Logarithmic Decrement Plot - SVS-9 Maneuver 2-4 (Z Axis)
Figure B.37: SVS-9 Maneuver 2-4 Power Spectral Density (Y Axis)

Figure B.38: SVS-9 Maneuver 2-4 Power Spectral Density (Z Axis)
Table B.7: Fundamental Natural Frequencies and Viscous Equivalent Damping Decrement ($\delta$) for SRMS Reference Position #2 (Maneuver 4)

<table>
<thead>
<tr>
<th></th>
<th>X-Axis</th>
<th>Y-Axis</th>
<th>Z-Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>0.209</td>
<td>0.179</td>
<td>0.179</td>
</tr>
<tr>
<td>Frequency (rad/s)</td>
<td>1.31</td>
<td>1.12</td>
<td>1.12</td>
</tr>
<tr>
<td>Damping Decrement, $\delta$</td>
<td>-0.012</td>
<td>-0.009</td>
<td>-0.004</td>
</tr>
</tbody>
</table>

Note: The $X$ component of the oscillation is much smaller than the $Y$ and $Z$ components but does appear to have a higher frequency.
B.3 SRMS Position #3

B.3.1 Maneuver 3.1

Figure B.39: SVS-9 Maneuver 3-1 (3 Axes) with Roll 19.48 and Yaw 6.597
Figure B.40: SVS-9 Maneuver 3-1 (X Axis) with Roll 19.48 and Yaw 6.597

Figure B.41: Logarithmic Decrement Plot - SVS-9 Maneuver 3-1 (X Axis)
Table B.8: Fundamental Natural Frequencies and Viscous Equivalent Damping Decrement (δ) for SRMS Reference Position #3 (Maneuver 1)

<table>
<thead>
<tr>
<th></th>
<th>X-Axis</th>
<th>Y-Axis</th>
<th>Z-Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>0.226</td>
<td>0.282</td>
<td>0.282</td>
</tr>
<tr>
<td>Frequency (rad/s)</td>
<td>3.53</td>
<td>1.77</td>
<td>1.77</td>
</tr>
<tr>
<td>Damping Decrement, δ</td>
<td>-0.075</td>
<td>-0.025</td>
<td>-0.048</td>
</tr>
</tbody>
</table>

Figure B.42: SVS-9 Maneuver 3-1 Power Spectral Density (X Axis)
B.3.2 Maneuver 3.2

Figure B.43: SVS-9 Maneuver 3-2 (3 Axes) with Roll 19.48 and Yaw 0.555
Figure B.44: SVS-9 Maneuver 3-2 (X Axis) with Roll 19.48 and Yaw 0.555

Figure B.45: Logarithmic Decrement Plot - SVS-9 Maneuver 3-2 (X Axis)
Table B.9: Fundamental Natural Frequencies and Viscous Equivalent Damping Decrement ($\delta$) for SRMS Reference Position #3 (Maneuver 2)

<table>
<thead>
<tr>
<th></th>
<th>X-Axis</th>
<th>Y-Axis</th>
<th>Z-Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>0.219</td>
<td>0.131</td>
<td>0.219</td>
</tr>
<tr>
<td>Frequency (rad/s)</td>
<td>1.38</td>
<td>0.823</td>
<td>1.38</td>
</tr>
<tr>
<td>Damping Decrement, $\delta$</td>
<td>-0.010</td>
<td>-0.004</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Figure B.46: SVS-9 Maneuver 3-2 Power Spectral Density (X Axis)
B.3.3 Maneuver 3.3

Figure B.47: SVS-9 Maneuver 3-3 (3 Axes) with Roll 19.48 and Yaw 0.555
Figure B.48: SVS-9 Maneuver 3-3 (Y Axis) with Roll 19.48 and Yaw 0.555

Figure B.49: Logarithmic Decrement Plot - SVS-9 Maneuver 3-3 (Y Axis)
Figure B.50: SVS-9 Maneuver 3-3 (Z Axis) with Roll 19.48 and Yaw 0.555

Figure B.51: Logarithmic Decrement Plot - SVS-9 Maneuver 3-3 (Z Axis)
Figure B.52: SVS-9 Maneuver 3-3 Power Spectral Density (Y Axis)

Figure B.53: SVS-9 Maneuver 3-3 Power Spectral Density (Z Axis)
Table B.10: Fundamental Natural Frequencies and Viscous Equivalent Damping Decrement ($\delta$) for SRMS Reference Position #3 (Maneuver 3)

<table>
<thead>
<tr>
<th></th>
<th>X-Axis</th>
<th>Y-Axis</th>
<th>Z-Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>0.153</td>
<td>0.153</td>
<td>0.153</td>
</tr>
<tr>
<td>Frequency (rad/s)</td>
<td>0.961</td>
<td>0.961</td>
<td>0.961</td>
</tr>
<tr>
<td>Damping Decrement, $\delta$</td>
<td>0.064</td>
<td>-0.027</td>
<td>-0.027</td>
</tr>
</tbody>
</table>

Note: The positive decrement in the $X$ component results from cross-coupled energy leaking from the large $Y$ and $Z$ components into the much smaller $X$ component.
B.3.4 Maneuver 3.4

Figure B.54: SVS-9 Maneuver 3-4 (3 Axes) with Roll 19.48 and Yaw 0.555
Figure B.55: SVS-9 Maneuver 3-4 (Y Axis) with Roll 19.48 and Yaw 0.555

Figure B.56: Logarithmic Decrement Plot - SVS-9 Maneuver 3-4 (Y Axis)
Figure B.57: SVS-9 Maneuver 3-4 (Z Axis) with Roll 19.48 and Yaw 0.555

Figure B.58: Logarithmic Decrement Plot - SVS-9 Maneuver 3-4 (Z Axis)
Figure B.59: SVS-9 Maneuver 3-4 Power Spectral Density (Y Axis)

Figure B.60: SVS-9 Maneuver 3-4 Power Spectral Density (Z Axis)
Table B.11: Fundamental Natural Frequencies and Viscous Equivalent Damping Decrement $\delta$ for SRMS Reference Position #3 (Maneuver 4)

<table>
<thead>
<tr>
<th></th>
<th>X-Axis</th>
<th>Y-Axis</th>
<th>Z-Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency (Hz)</strong></td>
<td>0.156</td>
<td>0.156</td>
<td>0.156</td>
</tr>
<tr>
<td><strong>Frequency (rad/s)</strong></td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td><strong>Damping Decrement, (\delta)</strong></td>
<td>0.008</td>
<td>-0.004</td>
<td>-0.004</td>
</tr>
</tbody>
</table>

Note: The positive decrement in the $X$ component results from cross-coupled energy leaking from the large $Y$ and $Z$ components into the much smaller $X$ component.
Appendix C

Characterization Plots

The following are probability distributions of measurements made to determine the measurement latencies inherent in the ASVS photogrammetric and data transmission processes.
Figure C.1: Latency (ASVS only) Test Data Probability Distribution.
Figure C.2: Precision Test Data Probability Distribution.
Appendix D

Camera Specifications

The following camera parameters are included as a reference for future work on this project. Additional cameras added to the visual servo loop should have identical synchronization parameters and resolution. Note: The ASVS Video Sampling Processor and Cohu cameras both synchronize off the leading edge of the video synchronization pulse; Hitachi and Canon systems, on the other hand, synchronize off the trailing edge.
4910 SERIES
RS-170 AND CCIR
MONOCHROME CCD CAMERAS
### Table 1. Specifications

<table>
<thead>
<tr>
<th><strong>ELECTRICAL</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Image Area</td>
<td>6.4 x 4.8 mm (corresponding to a 1/2-in. image tube)</td>
</tr>
<tr>
<td>Active Picture Elements</td>
<td>RS-170 768 (H) x 494 (V) 752 (H) x 582 (V)</td>
</tr>
<tr>
<td>Imager Type</td>
<td>HAD interline transfer CCD</td>
</tr>
<tr>
<td>Cell Size</td>
<td>RS-170 8.4 (H) x 9.8 (V) microns 8.6 (H) x 8.3 (V) microns</td>
</tr>
<tr>
<td>Resolution (TV lines)</td>
<td>RS-170 580 horizontal, 350 vertical 560 horizontal, 450 vertical</td>
</tr>
<tr>
<td>Sensitivity, 2654 K°</td>
<td>See table 1a</td>
</tr>
<tr>
<td>Electronic Shutter</td>
<td>Eight steps. OFF (1/60, 1/50), 1/125, 1/250, 1/500, 1/1000, 1/2000, 1/4000, 1/10,000 second</td>
</tr>
<tr>
<td>Integration</td>
<td>Field (1/60, 1/50) or frame (1/30, 1/25), internally jumper selectable Controllable period through external input pulse Grab pulse output</td>
</tr>
<tr>
<td>Video output</td>
<td>1.0 V p-p, 75 ohm, unbalanced</td>
</tr>
<tr>
<td>Gamma</td>
<td>Continuously variable 0.45 to 1.0</td>
</tr>
<tr>
<td>Agc</td>
<td>26 dB (variable gain)</td>
</tr>
<tr>
<td>Signal-to-Noise Ratio</td>
<td>56 dB, gamma 1, gain 0 dB 38 dB, gamma 1, agc maximum gain</td>
</tr>
<tr>
<td>Auto Lens</td>
<td>Separate lens video output eliminates agc/auto-iris lens interaction (peak/average adjustable) Lens power output -15 V dc, 35 mA maximum</td>
</tr>
<tr>
<td>Sync</td>
<td>Genlock, revert to variable phase line lock, zero crossing detector Genlock, revert to crystal* Crystal lock Asynchronous reset Internal clock: 28.6363 MHz RS-170(A) or 28.375 MHz CCIR *Genlock Includes H and V Drive inputs</td>
</tr>
<tr>
<td>Input Power</td>
<td>12 V ac/dc (standard) 24 V ac/dc optional 115 V ac, 60 Hz (optional on RS-170 models. Wall transformer with cable provides 12 V ac to Camera) 230 V ac, 50 Hz (optional on CCIR models. Wall transformer with cable provides 12 V ac to Camera) 4.2 watts dc power consumption Green LED power indicator (Also serves as electronic iris setup indicator)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>MECHANICAL</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>See figure 1</td>
</tr>
<tr>
<td>Weight, less lens</td>
<td>520 grams (18.5 oz)</td>
</tr>
<tr>
<td>Lens Mount</td>
<td>CS or C mount, 16-mm format CS-mount adapter provided 5-mm extension ring provided for adapting to C-mount lenses</td>
</tr>
<tr>
<td>Camera mount</td>
<td>1/4-20 threaded holes top (1) and bottom (2)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>ENVIRONMENTAL</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Temperature Limits</td>
<td>Operating: -20 to 60 °C (4 to 140 °F) Storage: -30 to 70 °C (-22 to 158 °F)</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>Up to 95%, noncondensing</td>
</tr>
<tr>
<td>Vibration</td>
<td>Sine vibration from 5 to 60 Hz with 0.082 inch total excursion (15 g’s at 60 Hz) Random vibration from 60 to 1,000 Hz, 5 g’s rms (0.027 g²/Hz) without damage</td>
</tr>
</tbody>
</table>
COMPLIES WITH FEDERAL COMMUNICATIONS COMMISSION
RULES AND REGULATIONS
PART 15 FOR CLASS B DIGITAL DEVICE

NOTE: This equipment has been tested and found to comply with the limits for a Class B digital device, pursuant to part 15 of the FCC rules. These limits are designed to provide reasonable protection against harmful interference in a residential installation. This equipment generates, uses and can radiate radio frequency energy and, if not installed and used in accordance with the instruction manual, may cause harmful interference to radio or television reception, which can be determined by turning the equipment off and on. The user is encouraged to try to correct the interference by one or more of the following measures:

1. Reorient or relocate the receiving antenna.
2. Increase the separation between the equipment and the receiver.
3. Connect the equipment into an outlet on a circuit different from that to which the receiver is connected.
4. Consult the dealer or an experienced radio/TV technician for help.

Changes or modifications not expressly approved by the party responsible for compliance could void the user’s authority to operate the equipment.

SENSOR SPECTRAL RESPONSE

IR BLOCKING FILTER RESPONSE

TYPICAL t/STOP VS. SHUTTER SPEED FOR EQUIVALENT LIGHT AT SENSOR FACEPLATE
Table 1. Faceplate Sensitivity

<table>
<thead>
<tr>
<th>Sensitivity</th>
<th>Full Spectrum</th>
<th>With IR Blocking Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Video, No Agc</td>
<td>0.065 fc (0.65 lux)</td>
<td>0.25 fc (2.5 lux)</td>
</tr>
<tr>
<td>80% Video, Agc On</td>
<td>0.002 fc (0.02 lux)</td>
<td>0.01 fc (0.1 lux)</td>
</tr>
<tr>
<td>30% Video, Agc On</td>
<td>0.0004 fc (0.004 lux)</td>
<td>0.0015 fc (0.015 lux)</td>
</tr>
</tbody>
</table>

Note: Sensitivity in the non-interlaced frame mode will be one-half the values given in the table.

Table 2. Model Number Interpretation

<table>
<thead>
<tr>
<th>Model Number Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>491 XXXXX XX XX XX XX XX</td>
</tr>
<tr>
<td>POWER</td>
</tr>
<tr>
<td>OPTICAL FILTER</td>
</tr>
<tr>
<td>VIDEO FORMAT</td>
</tr>
<tr>
<td>OPTION</td>
</tr>
<tr>
<td>LENS OPTIONS</td>
</tr>
<tr>
<td>Manual Iris, CS Mount</td>
</tr>
<tr>
<td>Manual Iris, C Mount</td>
</tr>
<tr>
<td>Auto Iris, CS Mount</td>
</tr>
<tr>
<td>Auto Iris, C Mount</td>
</tr>
<tr>
<td>AO03 3.7mm f/1.6, 1/2&quot;</td>
</tr>
<tr>
<td>AO05 6mm f/1.4, 1/2&quot;</td>
</tr>
<tr>
<td>AO13 12mm f/1.4, 1/2&quot;</td>
</tr>
<tr>
<td>AL04 &quot;4.5mm f/2.0, 2/3&quot;</td>
</tr>
<tr>
<td>AL08 &quot;8mm f/1.4, 2/3&quot;</td>
</tr>
<tr>
<td>AL16 &quot;16mm f/1.4, 2/3&quot;</td>
</tr>
<tr>
<td>AL25 25mm f/1.4, 1&quot;</td>
</tr>
<tr>
<td>AL50 25mm f/1.4, 1&quot;</td>
</tr>
<tr>
<td>AL75 75mm f/1.8, 1&quot;</td>
</tr>
<tr>
<td>&quot;Wide angle</td>
</tr>
<tr>
<td>EH04 3.7mm f/1.6, 1/2&quot;</td>
</tr>
<tr>
<td>EH06 6mm f/1.4, 1/2&quot;</td>
</tr>
<tr>
<td>EH13 12mm f/1.4, 1/2&quot;</td>
</tr>
<tr>
<td>ES04 4.2mm f/1.8, 1/2&quot;</td>
</tr>
<tr>
<td>ES05 4.8mm f/1.8, 2/3&quot;</td>
</tr>
<tr>
<td>ES08 8mm f/1.4, 2/3&quot;</td>
</tr>
<tr>
<td>ES12 12.5mm f/1.4, 2/3&quot;</td>
</tr>
<tr>
<td>ES16 16mm f/1.4, 2/3&quot;</td>
</tr>
<tr>
<td>ES25 25mm f/1.4, 1&quot;</td>
</tr>
<tr>
<td>ES35 35mm f/1.4, 2/3&quot;</td>
</tr>
<tr>
<td>ES50 50mm f/1.4, 1&quot;</td>
</tr>
<tr>
<td>EH35 75mm f/1.8, 1&quot;</td>
</tr>
</tbody>
</table>

(Note: With the electronic iris option installed and turned on, only a manual-iris lens can be used. Also, to use this option, the camera internal jumper must be positioned to the standard field mode, and turning on the electronic iris prevents use of the side panel shutter speeds.)
1.0 ELECTRICAL CHARACTERISTICS

The 4910 monochrome Camera uses a 1/2-inch format HAD interline transfer sensor. This sensor offers lower dark current, image lag, and blooming than other types of sensors. It has improved dynamic range and spectral characteristics, too. A 1000:1 overload capacity prevents bright incidental light in a scene from deteriorating the video. The agc has a 20-dB range. See table 1 for a complete listing of specifications.

Field transfer is the normal operating mode but frame transfer can be selected with an internal repositional jump. Section 13 describes differences between these two operating modes.

The Camera is available in RS-170 and CCIR versions. See table 2 for a model number interpretation chart.

When an RS-170 version of the Camera operates with internal crystal as the sync reference source, its field rate is 59.94 Hz. This is consistent with RS-170(A) specifications, making the Camera compatible with field and line rates for color systems. When genlocked the Camera operates at whatever field rate the input pulse supplies.

A line-locked RS-170 version of the Camera operates at a 60-Hz field rate; a line-locked CCIR version operates at 50 Hz.

On the rear panel, a screwdriver adjustment for line-lock PHASE provides 180-degree control range. If additional adjustment range is required, the low-voltage ac power input leads to the rear panel can be reversed to provide a 180-degree phase shift.

A side-panel trim plate can be removed to access seven controls and switches.

An optional electronic iris automatically operates the electronic shutter smoothly through a light control range from 1/60 (1/50) to 1/10,000 second, a seven-stop range. This option is used with a manual iris lens so that an auto-iris lens is not required. The electronic iris can be switched on and off with the side panel ELECT IRIS switch. When this switch is OFF, the electronic shutter is manually controllable by another side-panel switch. It can be set to any of eight positions from OFF (1/60, 1/50) to 1/10,000 second.

Integration is controlled by application of a control pulse input on the rear panel AUX (auxiliary) connector. Two other pins of this connector provide a complementary grab-pulse output.

When internal jumpers are set to the reset (not normal/genlock) mode, the Camera can be asynchronously reset at any time by application of a reset pulse to the AUX connector at pin 6. This initiates a vertical-blanking interval 2.5 microseconds later. Video output from the BNC connector then follows the vertical blanking interval, which, for RS-170, is about 1.2 milliseconds (19 to 21 lines) wide. For CCIR, vertical blanking is about 1.6 milliseconds wide (25 lines). If in field mode, this first field of video will most likely be of reduced video level because the reset pulse will have cut the sensor integration period short. Subsequent fields will have a normal video level.

If in frame mode, the first two fields making up an interlaced frame will likely be of reduced (and different) video levels. Subsequent fields making up the frames, though, will be of normal video level.

2.0 MECHANICAL CHARACTERISTICS

See figure 1 for dimensions. Figure 2 shows a top view of the Camera with most of the case cut away. The majority of circuits for the Camera

![Figure 2. Circuit Board Locations](image-url)
mount on two vertically oriented boards interfacing through hinged connectors to the sensor board at the front. The two boards are secured at the rear by the rear panel.

The optional electronic iris circuit board mounts to two connectors on the video/sync board.

The sensor board mounts to four pads inside the back of the front casting. In front of the sensor board is either a clear glass window or the optional IR blocking filter. The response of this IR filter is shown in the chart accompanying the specifications in Table 1.

At the front of this casting is a circular opening threaded to accept a 1.250-32 UNC-2A lens mount adapter. The Camera is supplied with an adapter of a width intended for use with C-mount lenses. Using C-mount lenses with this adapter requires that a 5-mm extension ring be installed on the CS-mount adapter. This 5-mm ring is supplied with the Camera.

Opposite each other, at the top and bottom of the front casting, are threaded holes to accept 1/4-20 UNC-2A mounting bolts. On the bottom of the Camera is a second 1/4-20 threaded hole, 1.5 inch (38.1 mm) to the rear of the front mounting hole in the casting.

The left side of the case has seven holes down its length for access to certain switches and adjustments on the video/sync board. A protective trim strip, held in place by a 2-56 x 1/8 flathead screw, covers these holes when access is not required.

All interconnections with the Camera are made on the rear panel. Table 3 lists part numbers for each of these rear panel connectors and also supplies part numbers for the mating cable connectors. Both the factory part number and a part number from an alternate source are given. This alternate number is either the part number from a manufacturer of that connector or the part number from an alternate supply source.

3.0 POWER REQUIREMENTS

Input power applied to the Camera rear panel connector routes through filtering to a bridge rectifier.

Optoisolators and a flyback transformer in the Camera isolate power input circuits from other circuits in the Camera. This has the same effect as an isolation transformer on the input. The advantage to this isolation is that it allows multiple Cameras to be operated from a single 12 V ac source.

Power input to a standard version of the Camera is 12 V ac or +12 V dc. (A 24-volt option is available.)

With ac input to the rear panel, an RS-170 version must receive 60-Hz power, a CCIR version 50 Hz. Operation in line-lock mode requires that low voltage ac power be applied to the rear panel of the camera.

Power input leads can be applied to either input without regard to polarity. (When setting up operation in the line-lock mode, it is sometimes necessary to switch the two leads at the rear panel so that the ac input is reversed 180 degrees in phase. See section 11.0.)

If a 12-volt version of the Camera is to be operated from ac line power, optional plug-in wall transformers are available to step down the line voltage to 12 V ac. Both 115-V ac 60-Hz and 230-V ac 50-Hz plug-in wall transformers are available for use with corresponding versions of the Camera.

If the Camera is to operate from a 12-V ac or dc power supply, the supply leads must have a 1/2-amp time-lag fuse in series.

If a Camera with the 24-V ac/dc option is to operate from a 24 volt power supply, the power lead must have a 1/4-amp time-lag fuse in series.

A rear panel lamp indicates when power has been applied to the power input connector. This

<table>
<thead>
<tr>
<th>NAME</th>
<th>CAMERA REAR PANEL CONNECTOR</th>
<th>MATING CONNECTOR FOR CABLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUX (J21)</td>
<td>1310373-008 8 Pin Mini DIN Jack</td>
<td>1310373-108 8 Pin Mini DIN Plug</td>
</tr>
<tr>
<td>LENS (J37)</td>
<td>1310375-003 3 Pin Mini DIN Jack</td>
<td>Hosiden TCS7537-01-201</td>
</tr>
<tr>
<td>POWER (J25)</td>
<td>1310378-001</td>
<td>Weco 180-A-111/02</td>
</tr>
<tr>
<td>VIDEO (J32)</td>
<td>BNC Jack</td>
<td>BNC Plug</td>
</tr>
</tbody>
</table>

Table 3. Rear Panel Interfacing Connectors
lamp also serves to adjust the manual iris lens when setting up the optional electronic iris feature. It can be made to go on and off during the setup.

4.0 EQUIPMENT SUPPLIED

The following list does not include any optional or special-request items. A lens ordered with the Camera will either be installed on or packed with the Camera. The mating lens connector is attached to the cable.
1. Camera, 4910 series
3. Adapter, CS-mount
4. Ring, extension, 5 mm, CS to C mount
5. Plug, auxiliary connector (for J21 on rear panel)
6. Plug, lens connector (for J37 on rear panel)

5.0 EQUIPMENT REQUIRED BUT NOT SUPPLIED

The first two items are the minimum required to make use of the Camera. These items are listed in the model breakdown for the Camera and are typically ordered and supplied at the time of purchase. Items 3 and 4 are optional items required to take advantage of Camera capabilities.

The frame grabber is required to use the integration feature. To make use of integration, a start/stop pulse must be supplied to the Camera. The Camera then provides as an output a grab-pulse for use by the frame grabber.
1. Lens, TV type, C-mount or CS-mount (When using the optional electronic iris circuit, a manual iris lens is required)
2. Power supply, ac or dc
3. Sync reset source, asynchronous
4. Frame grabber, with integrate start/stop pulse output and grab-pulse input

6.0 UNPACKING AND RECEIVING INSPECTION

This item was thoroughly tested and carefully packed in the factory. Upon acceptance by the carrier, they assume responsibility for its safe arrival. Should you receive this item in a damaged condition, apparent or concealed, a claim for damage must be made to the carrier. To return the product to the factory for service, please contact the Customer Service Department for a Return Authorization Number.

If a visual inspection shows damage upon receipt of this shipment, it must be noted on the freight bill or express receipt and the notation signed by the carrier's agent. Failure to do this can result in the carrier refusing to honor the claim.

When the damage is not apparent until the unit is unpacked, a claim for concealed damage must be made. Make a mail or phone request to the carrier for inspection immediately upon discovery of the concealed damage. Keep all cartons and packing materials. Since shipping damage is the carrier's responsibility, the carrier will furnish you with an inspection report and the necessary forms for filing the concealed-damage claim.

7.0 STATIC DISCHARGE PROTECTION

Components used in modern electronic equipment, especially solid state devices, are susceptible to damage from static discharge. The relative susceptibility to damage for semiconductors varies from low with TTL to high with CMOS. Most other semiconductors fall between TTL and CMOS in susceptibility to static discharge.

As a minimum, therefore, observe the following practices when working inside this or any other electronic equipment:
1. Use conductive sheet stock on the work bench surface
2. Connect the sheet stock to ground through a 1 megohm or greater value resistor
3. Use a wrist strap connected to ground through a 1 megohm or greater value resistor when working at the bench
4. Maintain relative humidity of the room above 30 percent. This may require a room humidifier. Working on circuits when relative humidity is below 30 percent requires extraordinary procedures not listed here
5. Use anti-static bags to store and transport exposed chassis, circuit boards, and components. Use new anti-static bags. Old, used bags lose their static protection properties

This list serves as a reminder of the minimum acceptable practices. Be sure that all static discharge devices at the work bench are properly installed and maintained.
Standard grounding sheets and wrist straps purchased for use at work benches are supplied with leads having the required current limiting resistors for safety. Never substitute with a lead that does not have a resistor.

8.0 INSTALLATION PROCEDURE

This summary of the installation procedure assumes that the Camera may not be properly set up for the intended application. Internal jumpers may have to be repositioned and side panel controls may require new settings while the camera is at a work bench. The Camera is then turned on so that back focus (CS-mount adjustment) can be checked out before mounting at its permanent location. If the Camera is known to be properly set up for the intended application, only steps 8 through 11 need be performed.

Additional information about these procedures follows this summary of the installation procedure. Do not begin the installation without referencing the subsequent sections that provide detailed instructions about the installation. Figure 3 shows the Camera rear panel, where all interconnections are made.

A typical installation includes:

1. Installing the required power, video, and auxiliary connector cables between the Camera location and the operator's console or equipment room.
2. Removing the case and setting up internal jumpers for the desired operating conditions.
3. Installing the lens (and, for an auto iris lens, connecting the lens video cable).
4. Connecting power and video (and if required sync).
5. Checking back focus and adjusting the lens mount adapter if necessary.
6. Setting up side panel controls for the intended application (if required).
7. Removing power, video, and sync cables.
8. Mounting the Camera at its location.
9. Connecting power, video, and any other required cables.
10. Adjusting the Camera and lens to view the scene of interest.
11. Making any required final adjustments to side panel controls, the rear-panel line-lock PHASE adjustment, and the manual-iris lens if the electronic iris option is being used.

8.1 Power Connections

Do not apply voltage outside the recommended operating range of the Camera (12 V ac/dc ±10%, or 24 V ac/dc ±10%, depending on the option.)

The Camera requires either 12 V ac/dc or optionally 24 V ac/dc ±10%. A 12-volt version of the Camera operates from 115 V ac, 60 Hz (or 230 V, 50 Hz) power by using an optional external plug-in wall transformer (figure 4). If the Camera is to operate from a power supply other than the optional wall transformers, use a 0.5-amp time-lag fuse (0.25-amp time-lag fuse with the 24-volt version of the Camera).

When fluorescent lighting will be used to illuminate the scene being viewed by the camera during electronic iris operation, line lock mode must be used. This requires that the camera be operated from 12 V ac (or the optional 24 V ac) input power at the rear panel.

8.2 Video Connections

Standard 1-volt peak-to-peak composite video is available at the rear panel BNC connector (figure 5). This is a standard 75-ohm ac coupled video output. Use 75-ohm coaxial cable. A 75-ohm termination must be used at the equipment connected to this
cable. When multiple equipment is connected to the video output in a loop-through arrangement, only the last item of equipment at the end of the cable should be terminated. All other equipment must present a high impedance to the cable.

8.3 Genlock Inputs

Applying composite sync (sync containing both horizontal sync and vertical sync pulses) to pin 2 of the AUX connector (figure 6) takes control of the Camera away from the internal sync reference. (The internal reference is either the crystal or the line-lock reference. Line lock can be used only if the Camera is operating from low voltage ac at the rear panel.)

Figure 4. Power Supply

When the Camera genlock input is on a cable with other Cameras (or video equipment), only the Camera or equipment at the end of the cable away from the sync source can have its internal 75-ohm termination selected. If the Camera is mid-cable in such an arrangement, be sure that jumper JB80 on the genlock/power-supply board is removed. Removing the jumper allows the input to become a high impedance instead of 75 ohms. This jumper can be stored by plugging it onto only one pin.

The Camera can also be connected to a sync reference consisting of horizontal-trigger pulses applied to pin 2 on the AUX connector and vertical triggering pulses applied to pin 1.

Figure 5. Video Output Connector (J32)
8.4 Asynchronous Input

Repositionable jumpers on the video/sync board must be positioned to RST (reset) when the asynchronous reset feature to be used. It cannot be used if the jumpers are positioned to the NOR (normal) mode, which is genlock.

An asynchronous reset is initiated when pin 6 of the AUX connector is pulled low (below 1.7 volt). The vertical interval of the Camera then resets 2.5 microseconds later (figure 7). Note that the minimum allowable width of the reset pulse is 1 microsecond.

Since application of the reset pulse most likely interrupts the sensor before the end of an integration period, the first field of video out of the Camera following reset will be of a reduced video level. (If operating in the interlaced frame mode, the second field will also have a reduced level.) Subsequent fields would then be of normal video levels.
8.4.1 Strobing with Asynchronous Input

To capture rapidly moving or periodic events, a strobe light can be used in conjunction with an asynchronously reset camera. The camera should be operated in frame mode so that both fields are produced by the strobe. See section 13 for a description of field and frame modes.

This strobe can occur during either of two periods (figure 8) following application of the reset pulse:

1. Beginning 2.5 μs after application of the reset pulse and throughout a 9 horizontal-line interval (14.5 H for CCIR) until a transfer gate occurs. This is a strobing window of about 572 (928) microseconds.

2. Beginning 9.5 H (15 H for CCIR) after the vertical drive is reset and continuing throughout a full vertical interval — 1/60 (1/50) second — until the next transfer gate occurs.

Figure 8 also shows the related fields of video produced by a strobe during either of these two strobe periods.

Captions accompanying the waveform in figure 8 more fully describe their relationships. For a detailed view of the 2.5 μs delay between application of the asynchronous reset pulse and the start of a new vertical drive see figure 7. It expands this timing area to show both the 2.5 μs delay and the required 1 μs minimum duration for the asynchronous reset pulse.

Ambient Light Considerations

When planning to use a strobe light with the camera, some consideration should be given to ambient lighting on the scene and to the setting of the lens iris. When the camera is asynchronously reset, any image integrated on the sensor up to that time becomes part of the video output. This will be both fields if in frame mode and a single field if in field mode.

Ideally the camera should not produce any picture unless the strobe is triggered. This would require a nearly dark scene. As a practical matter, it is likely that some picture can be allowed to appear before it produces unacceptable interference with the strobe light image. A few tests will determine whether the image generated by ambient light produces unacceptable interference with the desired strobe light image.

8.5 Integration Input and Output

When pin 8 of the AUX connector is pulled low, integration begins with the next vertical blanking pulse. When the input is allowed to go high again, integration ends with the next vertical blanking pulse. Note in figure 9 that integration begins and ends with the vertical blanking interval — not at the exact time of application and removal of the integration pulse. The minimum integration period is two fields. The maximum period is about four to six seconds, limited by deterioration of picture quality caused by dark current. It is best to perform tests to determine acceptable picture quality vs. integration period for an intended application.

For applications requiring longer integration periods, maintaining the Camera (sensor) at reduced temperatures will enhance picture quality by reducing noise.

8.6 Lens Installation

Figure 10 shows spacing of a CS-mount lens and a C-mount lens in relation to the focal plane of the sensor. Note that the 5-mm adapter ring positions the mounting shoulder of a C-mount lens 5 mm farther away from the sensor. A CS-mount lens focuses 12.5 mm away from its shoulder. A C-mount lens focuses 17.5 mm away.

The mounting shoulder is the surface of the lens that presses against the mounting adapter when it is fully threaded in.

If a CS-mount lens is to be installed, be sure that the 5-mm extension ring has been removed. For installation of a C-mount lens, be sure the 5-mm ring is in place. Proceed as follows:

1. Remove the protective plastic plug or seal from the lens mount adapter opening.

2. Clean the lens and the window in front of the image sensor. Use methyl alcohol or a commercially prepared optical-quality solution and a cotton swab. Never rub an optical surface with a dry swab.
NOTE: The following descriptions assume operation in frame mode. Since frame mode integrates both the odd and even fields simultaneously, a strobe of light produces a complete frame of video. (In field mode, however, odd and even fields are produced during separate vertical intervals; only a single field of video can result from a strobe.)

1. **ASYNCHRONOUS RESET PULSE** When this pulse is applied to pin 6 of J21, on the camera rear panel, the camera internal vertical drive resets. See waveform 2. (Though not detailed on this figure, a delay of 2.5 μs occurs between application of the reset pulse and internal vertical drive being reset. See figure 7 for an expanded view.)

2. **CAMERA INTERNAL VERTICAL DRIVE RESET.** When the camera internal vertical drive is reset, two time periods follow during which a strobe light may be triggered to illuminate the scene. In frame mode, both fields will be integrated by the sensor when this strobe occurs during either period.

   The first period starts 2.5 μs after reset and continues for 9 H (14.5 H for CCIR) lines. The shaded area in waveform 3 shows this first period.

   A transfer gate occurs in the interval reserved from 9 to 9.5 lines (14.5 to 15 lines for CCIR). This gate (TG1) initiates transfer of field 1 and then a second gate (TG2) initiates transfer of field 2 from the sensor to become video at the Camera rear panel BNC connector, J32. This is shown in waveform 3A. Be aware that ambient light on the scene may produce sufficient video to interfere with the image produced by the strobe.

   The second period starts 9.5 H lines (15 H lines for CCIR) after reset and continues for a full vertical interval of 1/60 (1/50) second. See waveform 4. The transfer gate at the end of this vertical interval then initiates movement of field 2 from the sensor to become video at the Camera rear panel BNC connector, J32. A second gate initiates movement of field 1 to this output. Waveform 4A shows field 2 followed by field 1. Vertical intervals and transfer gates then repeat until another asynchronous reset pulse is applied at pin J21-6.

3. **FIRST STROBE PERIOD.** After application of the asynchronous reset pulse and throughout an interval of 9 H lines (14.5 H lines for CCIR), the strobe light may be triggered to light the scene. Field 1 and field 2 are integrated simultaneously by the sensor. This results in the outputs shown in Waveform 3A.

3A. **OUTPUT FROM FIRST STROBE PERIOD.** Both fields are integrated by the sensor when the strobe is triggered during the first 9 H intervals (14.5 H intervals for CCIR) after asynchronous reset. TG1 transfers out field F1 and TG2 transfers out field F2 to provide video at the camera rear panel. Both fields may have residual image from ambient light.

4. **SECOND STROBE PERIOD.** This period begins 9.5 H intervals (15 H intervals for CCIR) after asynchronous reset and continues throughout a full vertical period of 1/60 (1/50) second. A strobe light triggered anytime during this period produces both fields on the sensor simultaneously. Waveform 4A shows the video outputs derived from the sensor as a result of a strobe light being triggered during this second period.

4A. **OUTPUT FROM SECOND STROBE PERIOD.** When the scene is strobed with light during the second strobe period, the first video out of the camera is field F2 — followed by field F1. Both fields may have residual image from ambient light.

Figure 8. Timing Diagram, Asynchronous Reset with Strobe Light Intervals
This distance is set by observing for sharp focus on a picture monitor. The lens focusing first must be set to infinity and the iris fully opened to establish minimum depth of field.

The adjustment can be performed either with a CS-mount lens installed in the CS-mount adapter or with a C-mount lens and 5-mm adapter installed in the CS mount.

Once back focus is set, it should be possible to change between most lens types without any further setting of back focus.

The first four steps determine whether any adjustment is required. Proceed as follows.

1. Set the lens focusing ring to infinity.

2. Point the Camera at a distant scene well into the infinity focusing distance of the lens.

3. Place sufficient neutral density (ND) filters in front of the lens so the lens iris is fully open with normal video output.

4. Note whether the scene is in sharp focus. If it is, no adjustment is required.

3. Check the setscrew and make sure it is snugged down. Be careful not to over-tighten.

4. Screw the lens into the adapter. Snug down so the two will turn as one unit when the setscrew is loosened for focus adjustments.

5. If an auto lens is used, plug the lens cable (P37) into the lens connector (J37) on the rear panel (figure 11).

8.7 Back Focus Adjustment

Back focus adjustment establishes proper distance between the back of the lens and the sensor. This ensures that the lens projects its image exactly on the surface (focal plane) of the sensor and not slightly in front of or behind the surface.

NOTE

The window in front of the sensor faceplate is out of the focal plane of the Camera. Thus small contaminants on this surface will most likely not show up in the picture. Even so, pressurized dry air should be used to remove any contaminants on the window or IR filter.

Figure 9. Timing Diagram, Integration

Figure 10. CS and C-Mount Adapters
5. If the scene is out of focus, loosen the setscrew and rotate the lens and adapter as a unit in and out of the Camera until the scene is in focus.

6. Snug down the setscrew. Do not over-tighten.

7. Verify that sharp focus is still maintained.

8.8 Auto Iris Lens Level

If an auto iris lens is used and the scene on a picture monitor has too much or too little contrast (or pulsates/hunts) under bright lighting conditions, the LEVEL control on the lens may require adjustment. To adjust this control, proceed as follows:

1. Set the side panel AGC switch to ON.

2. Set the auto iris lens PK/AVG (peak/average) control fully toward AVG.

3. Point the Camera at a brightly lighted scene having a full range of white and black levels.

4. Adjust the LEVEL control on the lens to obtain a normal picture on the picture monitor. When this control is properly set, video output at J32 to the monitor should be 1 Vp-p. (Virtually all lens manufacturers label this control LEVEL. If a lens is being used that does not have a control labeled LEVEL, adjust the control with a name similar to this function.)

5. Vary light level into the camera by placing a hand in front of the lens and taking it away. Do this several times while observing the picture monitor.

6. Note whether the light level of the scene on the picture monitor pulsates or hunts after the hand has been taken away. If pulsating/hunting is noted, proceed to step 7 for adjustment. If scene lighting remains stable, proceed to step 9.

7. Adjust the PK/AVG control on the auto iris lens slightly toward PK and repeat steps 5 and 6 until the pulsating/hunting stops. If it persists after several slight adjustments to the PK/AVG control, proceed to step 8.

8. Repeat steps 2 through 7. Make a slightly different adjustment to the LEVEL control in step 4 while maintaining a good picture on the picture monitor. After all conditions in these steps have been met, proceed to step 9.

9. Test the camera under actual operating conditions, if desired, and after verifying proper operation return it to service.

9.0 SIDE PANEL ADJUSTMENTS

Four adjustments and three switches appear under a panel on the left side of the Camera. They are described in table 4. Cameras are shipped with these controls set either for operation under typical conditions or as requested by the user. Black level would typically be set for the industry standard 7.5 IRE units (53 mV) above blanking. This can be changed under actual operating conditions to provide the desired picture from the Camera.

CAUTION
ELECTROSTATIC SENSITIVE DEVICES
DO NOT OPEN OR HANDLE EXCEPT AT A STATIC-FREE WORKSTATION

10.0 INTERNAL ADJUSTMENTS

Six repositionable jumpers are accessible when the case is removed from the Camera. Table 5 lists these jumpers and describes their functions. Their locations on the video-sync and genlock/power-supply boards are shown in figures 12 and 13.

Do not make any adjustments to components on the circuit boards when the case has been removed to reposition a jumper. Performing internal setup adjustments requires test instruments and detailed step-by-step procedures. Such procedures appear in section V of the Installation, Operation, and Maintenance Manual (6X-925). Perform internal setup adjustments...
Table 4. Side Panel Adjustments

<table>
<thead>
<tr>
<th>CONTROL NAME</th>
<th>NORMAL SETTING</th>
<th>FUNCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELECT IRIS ON/OFF (Requires the optional electronic iris board and a manual-iris lens)</td>
<td>ON</td>
<td>When turned ON, the electronic iris board provides automatic control of camera sensitivity to scene lighting through a range of about seven f/stops. It does this by electronically shuttering the sensor in the camera through a continuous range from 1/60 (1/50) second to 1/10,000 second. The iris on the manual-iris lens must be properly set. See section 12.0 for this adjustment. When the ELECT IRIS switch is set to ON, the eight-position shutter speed switch to the right is deactivated.</td>
</tr>
<tr>
<td>Shutter Speed Switch</td>
<td>As desired</td>
<td>Sets the shutter speed of the camera to any of its eight settings: from 1/60 (1/50) up to 1/10,000 second. Active only when ELECT IRIS switch at left is set to OFF.</td>
</tr>
<tr>
<td>PEAK/AVG</td>
<td>Midrange</td>
<td>When the related AGC ON/OFF switch is set to ON, this peak/average control determines whether the automatic gain control circuits respond more to peaks (highlights) of light in the scene or to the overall average light level. When this control is rotated toward the PEAK position, the agc holds the peaks in the video to a maximum of 100 IRE units. When adjusted to the AVG position, the agc averages the video to the 100-unit level.</td>
</tr>
<tr>
<td>GAIN</td>
<td>Midrange</td>
<td>When the related AGC ON/OFF switch is set to OFF, this control can provide an additional 20-dB gain for the camera. To minimize noise in the video, keep this control toward ccw. To increase gain (sensitivity to light), rotate this control clockwise. Noise increases as the control is rotated cw for more gain.</td>
</tr>
<tr>
<td>AGC ON/OFF</td>
<td>ON</td>
<td>Setting this switch to ON provides automatic gain control. Agc range is 20 dB. Setting the switch to OFF activates the related manual GAIN control.</td>
</tr>
<tr>
<td>GAMMA 1.0/.45</td>
<td>.45 for viewing 1.0 for measurement</td>
<td>Rotated fully cw to .45, this control provides a nonlinear video output that favors black areas of the scene at the expense of white areas. This setting compensates for a nonlinear characteristic common to all vacuum-type picture tubes used in standard monitors. Picture tubes favor whites over blacks. The net effect is that blacks and whites in the scene are accurately represented visually. This gamma control can be used to change tonal variations between blacks and whites when viewing scenes on a monitor. As the control is rotated ccw, away from the .45 position, the camera video output becomes less and less nonlinear. At the full ccw position (1.0) the video output is linear. Blacks and whites are represented electronically exactly as they appear in the scene. This is the setting to use for measurement purposes. Use 1.0 when connecting a frame grabber to the video output.</td>
</tr>
<tr>
<td>SHARPNESS</td>
<td>CCW</td>
<td>When adjusted clockwise, this control causes the peaks of the video signal to &quot;ring&quot;, or oscillate. This increases the contrast between the black/white and white/black transitions of the video signal. Adjust this control while viewing a monitor displaying camera video until the desired amount of sharpness is reached.</td>
</tr>
</tbody>
</table>
only when the step-by-step procedures in that manual are being followed. Be aware that adjusting anything electrical or mechanical without the proper procedure may void the warranty of a new Camera. Refer to the last page of this manual for the warranty.

11.0 REAR PANEL LINE-LOCK PHASE ADJUSTMENT

Multiple Cameras operating from 12 (or the optional 24) V ac input power can have their vertical intervals locked together by using the power line frequency as a reference. The internal crystal/line-lock (XTAL/LL) jumper on the video/sync board of all Cameras must be positioned to LL to use this feature.

Several situations can cause Cameras not to have their vertical intervals occurring at the same time when all are locked to the ac input power at the Camera rear panel.

1. Power input at the Camera rear panel may be 180 degrees out-of-phase relative to the Camera chosen as the reference. This is because the two leads at the power input connector are reversed in relation to the reference Camera.

2. Some Cameras may be operating off different phases of the main power line. This could position vertical intervals out-of-phase by, for example, 180 degrees or even 120 or 240 degrees relative to the power line.

3. Other phase shifts in power distribution equipment may be significant enough to cause problems in some applications.

Two actions can be performed at each Camera to put its vertical interval in phase with the vertical interval chosen as reference. (1) The rear panel PHASE control can be adjusted to provide up to 180 degrees of control. (2) If more than 180 degrees is required, the two power input leads can be reversed for a 180-degree phase shift. Then adjust the rear panel PHASE control for the final amount required.

The adjustment is generally done by observing video at the switcher where all the video cables converge. Use a dual-channel oscilloscope.

Video from one Camera is selected as the reference. Then the input power leads and PHASE controls on all other Cameras are changed as necessary to bring their vertical intervals into alignment with the reference Camera.

In summary, then:

1. Adjust the rear panel PHASE control for up to 180 degrees of control

2. Switch the two power leads at the rear panel when more than 180 degrees of control is required. Then make a final adjustment with the PHASE control.

12.0 ELECTRONIC-IRIS/ MANUAL-IRIS-LENS SETUP

When turned ON, the optional electronic iris board provides automatic control of Camera sensitivity to scene lighting through a range of about seven f/stops. It does this by electronically shuttering the sensor in the Camera through a continuous range from 1/10,000 second (scene very bright) to 1/60 (1/50) second (scene not well lighted). The manual iris lens must be set to bring the light handling capability of the electronic iris within range of the sensor.

For indoor use where scene lighting typically is not extremely bright and does not vary more than seven f/stops, the iris on the manual lens can usually be set wide open.

If fluorescent lights illuminate the scene, use line lock mode to prevent interference with the electronic-iris circuits.

For viewing a scene where the light is extremely bright and can vary more than seven f/stops (such as an outdoor scene), the iris on the manual lens must be stopped down somewhat. This is to bring the light reaching the sensor into a range that the electronic iris can handle. Proceed as follows to make this setting:

1. Verify that the Camera is viewing the scene of interest and that no further positioning adjustments are required.

2. Wait for the brightest time of day on the scene being viewed by the Camera.

3. Open the manual iris fully while observing the indicator lamp on the rear panel (fig. 3). As the lens is opened this lamp should go out at some point, indicating that the electronic iris has run out of range (and thus is at 1/10,000 s).

4. Slowly close the lens iris until the rear panel indicator just comes on again. This is the proper setting for the manual iris lens.

If blooming is observed on the picture monitor while using the electronic iris feature, it is likely that scene lighting has become too bright for the E.I. circuit.
Table 5. Repositionable Jumpers

<table>
<thead>
<tr>
<th>JUMPER</th>
<th>PURPOSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>JB1/XTA/ULL</td>
<td>Jumper position determines whether the default internal sync source is the internal crystal (RS-170(A) or CCIR) or the low voltage ac input power. Input power at the Camera rear panel connector must be ac for line lock to be used. A Camera operating with a genlock sync source will revert to either crystal or line lock (with ac input power) upon removal of the genlock input.</td>
</tr>
<tr>
<td>JB2, JB3 NOR/RESET</td>
<td>Positioning JB2 to NORmal selects genlock as the external sync source by activating pins 1 and 2 of the rear panel AUX connector. Positioning JB2 to RST activates the asynchronous vertical reset input (pin 6) of the rear panel AUX connector. In asynchronous mode, the Camera can be reset at any time by pulling pin 6 low. The Camera then provides video output immediately following a vertical blanking interval. Jumper JB3 is typically set to RST at all times. If desired it can be positioned to NOR when JB2 is set to NOR.</td>
</tr>
<tr>
<td>JB4 FRAME/FIELD</td>
<td>FIELD mode is the normal mode. In FIELD mode the sensor integrates for 1/60 (1/50) second. Two lines are summed and read out at a time until all pixels are read out. Although this reduces vertical resolution, it also minimizes lag and improves sensitivity. In FRAME mode, the sensor integrates for 1/30 (1/25) second and readout is the same as for a tube Camera. One row of pixels is read out for each horizontal line. FRAME mode gives the highest resolution, but lag and sensitivity are somewhat degraded.</td>
</tr>
<tr>
<td>J600 VD/PRE</td>
<td>This jumper position determines where the integration grab-pulse output begins. See figure 9. When positioned to PRE, the grab pulse starts at the same time the integration start/stop pulse goes low to end integration. Note in figure 9 that the integrated output from the Camera begins with the first vertical interval after leading edge of the grab pulse. When the jumper is positioned to V.D. (vertical drive), the grab pulse starts at the same time actual integration is ended. The grab pulse is coincident with the vertical-drive pulse at the end of integration.</td>
</tr>
<tr>
<td>JB80 75 Ohm Sync Sel.</td>
<td>With this jumper installed, the external sync/horizontal-trigger input (pin 2 of the AUX connector) is terminated with 75 ohms. This jumper should be removed only when the Camera is to be installed in a genlock cable with other Cameras. In this situation, only the last Camera (or other type of equipment) at the far end of the cable is terminated with 75 ohms. The disconnected jumper can be stored by installing it on only one pin of JB80.</td>
</tr>
</tbody>
</table>

13.0 OPERATING MODES

The four basic scanning modes are:
- Frame mode, interlaced
- Frame mode, non-interlaced
- Field mode, interlaced
- Field mode, non-interlaced

The Camera can be operated with non-interlaced scanning only when externally applied horizontal and vertical drive are used to establish a non-interlaced condition.

Timings appear first as RS-170 followed by CCIR timings in parenthesis.

Note in the two illustrations that a shutter interval is shown together with the integration time for fields 1 and 2. The long line is the integration time without shuttering. The boxed portion at the end of the long integration line is a representative integration period for shutter mode. The key point is that shuttering occurs near the end of a vertical interval.

13.1 Frame Mode — Interlaced

Refer to figure 14. In the interlaced frame mode, the sensor integrates each field for 1/30 (1/25) second — spanning two vertical intervals. Note that field-2 begins integrating midway through the integration of field-1.
Figure 12. Jumper Locations, Video/Sync Board

Figure 13. Jumper Location, Genlock/P.S. Board

Field-1 is comprised of odd lines, field-2 of even lines. In this mode pixels are not paired to form lines. Thus the maximum vertical resolution of about 485 (575) tv lines is available.

Since this mode integrates each field for 1/30 (1/25) second it is more prone to problems with relative movement between the Camera and scene.

13.2 Frame Mode — Non-interlaced

Refer to figure 14. Each field is scanned for 1/60 (1/50) second. Each field is integrated on the sensor during its own interval.

Only the odd lines are used. Vertical resolution is about 242 (287) tv lines. This is about one-half that available with the frame interlaced mode.

This mode has about one-half the sensitivity of the other three modes. Reduced sensitivity results due to the combination of integration occurring for 1/60 (1/50) second and pixels not being combine.

In the other three sensor operating modes, normal specified sensitivity is maintained due either to 1/30 second integration or to two lines of pixels being combined to form a single line.

13.3 Field Mode — Interlaced

Refer to figure 15. In the interlaced field mode, the sensor integrates for 1/60 (1/50) second and combines two rows of pixels to form the lines.

Note that to form field-1, pixels in lines one and two are combined. Then to form field-2 pixels in lines two and three are combined.

Because two lines of pixels are being combined to form each line, this mode provides the normal specified sensitivity, but it has less vertical resolution than the interlaced frame mode.
<table>
<thead>
<tr>
<th>FRAME SCANNING</th>
<th>INTERLACE</th>
<th>NON-INTERLACE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FIELD 1</td>
<td>FIELD 1</td>
</tr>
<tr>
<td></td>
<td>FIELD 2</td>
<td>FIELD 2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>INTEGRATION TIME</th>
<th>INTEGRATION TIME</th>
<th>FIELD 1</th>
<th>FIELD 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>VERTICAL DRIVE</td>
<td>FIELD 1</td>
<td>FIELD 2</td>
<td></td>
</tr>
<tr>
<td>VERTICAL DRIVE</td>
<td>FIELD 1</td>
<td>FIELD 2</td>
<td></td>
</tr>
<tr>
<td>VIDEO OUT</td>
<td>VIDEO OUT</td>
<td>VIDEO OUT</td>
<td>VIDEO OUT</td>
</tr>
<tr>
<td>VIDEO OUT</td>
<td>VIDEO OUT</td>
<td>VIDEO OUT</td>
<td>VIDEO OUT</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SENSITIVITY</th>
<th>NORMAL</th>
<th>ONE-HALF NORMAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>VERTICAL RESOLUTION - TV LINES</td>
<td>485(575)</td>
<td>242(287)</td>
</tr>
</tbody>
</table>

NOTE: WHEN ASYNCHRONOUSLY RESETTING WITH THE SHUTTER ON IN FRAME MODE, VIDEO OUTPUT OCCURS IN 1/50(1/50) SECOND.

**Figure 14. Frame Integration Mode**

<table>
<thead>
<tr>
<th>FIELD SCANNING</th>
<th>INTERLACE</th>
<th>NON-INTERLACE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FIELD 1</td>
<td>FIELD 1</td>
</tr>
<tr>
<td></td>
<td>FIELD 2</td>
<td>FIELD 2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>INTEGRATION TIME</th>
<th>INTEGRATION TIME</th>
<th>FIELD 1</th>
<th>FIELD 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>VERTICAL DRIVE</td>
<td>FIELD 1</td>
<td>FIELD 2</td>
<td></td>
</tr>
<tr>
<td>VERTICAL DRIVE</td>
<td>FIELD 1</td>
<td>FIELD 2</td>
<td></td>
</tr>
<tr>
<td>VIDEO OUT</td>
<td>VIDEO OUT</td>
<td>VIDEO OUT</td>
<td>VIDEO OUT</td>
</tr>
<tr>
<td>VIDEO OUT</td>
<td>VIDEO OUT</td>
<td>VIDEO OUT</td>
<td>VIDEO OUT</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SENSITIVITY</th>
<th>NORMAL</th>
<th>NORMAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>VERTICAL RESOLUTION - TV LINES</td>
<td>350(450)</td>
<td>242(287)</td>
</tr>
</tbody>
</table>

**Figure 15. Field Integration Mode**
This mode has less lag than the interlaced frame mode because of its 1/60 (1/50) second rate.

13.4 Field Mode — Non-interlaced

Refer to figure 15. In the non-interlaced field mode, the Camera operates at a 1/60 (1/50) second rate. The same two rows of pixels are combined to produce each line for both fields. This results in the lower vertical resolution of 242 (287) tv lines. Because two lines of pixels are combined to form each line, though, normal specified sensitivity is obtained.

CAUTION
SENSITIVE ELECTRONIC DEVICES
DO NOT SHIP OR STORE NEAR STRONG ELECTROSTATIC, ELECTROMAGNETIC, MAGNETIC OR RADIOACTIVE FIELDS

14.0 PREPARATION FOR SHIPMENT AND STORAGE

For storage periods exceeding about one month, seal the unit in a vapor-proof bag containing a fresh desiccant pack. Maintain the Camera storage environment within a range of -30 to 70 °C (-22 to 158 °F).

For shipment, package with enough foam padding or other packing material to prevent damage that can occur during shipping. The original shipping carton is a good container if it has not been damaged or subjected to excessive moisture.

For shipping to the factory by Common Carrier, use 5755 Kearny Villa Road, San Diego, CA 92123 as the address. Please contact the Customer Service Department for a Return Authorization (RA) number before sending any shipments to the factory.

WARRANTY

Cohu, Inc., Electronics Division, warrants equipment manufactured to be free from defects of material and workmanship. Any part or parts will be repaired or replaced when proven by Cohu examination to have been defective within two years from date of shipment to the original purchaser for standard CCD cameras and one year from date of shipment to the original purchaser for intensified CCD cameras and all other Cohu manufactured products.

All warranty repairs will be performed at the factory or as otherwise authorized by Cohu in writing. Transportation charges to Cohu shall be prepaid by purchaser.

This warranty does not extend to Cohu equipment subjected to misuse, accident, neglect, or improper application, nor repaired or altered by other than Cohu or those authorized by Cohu in writing. Television Image pickup tubes, Image Intensifiers, lenses, and products manufactured by companies other than Cohu are warranted by the original manufacturer. This warranty is in lieu of all other warranties expressed or implied. Cohu shall not be liable for collateral or consequential damages.

A Return Authorization (RA) number must be obtained from Cohu prior to returning any item for warranty repairs or replacement.

COHU
Cohu, Inc./Electronics Division

September 24, 1993
Revision 1 March 7, 1995