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ADDITIONAL SOFTWARE DEVELOPMENTS WANTED FOR MODELING AND CONTROL OF FLEXIBLE SPACE SYSTEMS

By

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ABSTRACT

Existing modeling and control software packages are either inadequate or inefficient for applications to flexible space structures. Some additional software developments are wanted for effective design and evaluation of the control systems. The following ~~will be~~ discussed, ~~in this presentation~~.

1. Linear-quadratic optimal regulators as usual can be designed using various "modern control" design software packages. To design for active augmentation of (approximately) the specified amount of active damping to each "controlled modes," the common practice is to adjust repeatedly the state and control weights (i.e., the Q and R matrices) by mostly endless trial and error. The time consumed and effort spent in the trial-and-error repetition can be saved by using an analytical procedure for closely estimating the corresponding state and control weights. ~~Various numerical examples have shown~~ that this is possible. No software has been developed for automating such a time-saving analytical assignment procedure yet.

2. "Modal dashpots" are very effective output-feedback vibration controllers for flexible structures, not only effective for augmenting a small amount of active damping to a large number of vibration modes (like the so-called low-authority structural controllers), but also effective for quick suppression of large vibrations (like high-authority structural controllers). Recent numerical results on orbital SCOLE configuration have shown so. No software has been developed for facilitating the design process yet.

3. The actual performance of any control design needs to be evaluated against a faithful model of the flexible structure to be controlled. The potential of destabilization or serious performance degradation needs to be detected by numerical simulation of the structure with the control loops being closed. Except for some trivial cases, reduced=order normal-mode models are generally not appropriate: if they are computationally feasible to simulate the closed-loop system, then they are likely not accurate enough to represent the dynamics of the flexible structure; if they are satisfactorily accurate, then they are mostly too large for effective dynamic simulation even by a state-of-the-art mainframe computer. ~~Besides, computing a very large number of normal~~ modes is very ~~expensive~~, and the accumulated computational errors in the natural frequencies and mode shapes grow very rapidly. The popular Guyan reduction technique is often used to reduce the large finite-element mass-stiffness model first. Such a reduction technique, unfortunately, introduces large additional errors which are proportional to the square of the natural frequency of the modes computed thereafter.

There is a trend towards some innovative use of non-normal modes (such as Ritz or Lanczos vectors) for representing the structures by a much smaller number of such modes. Available results are interesting and promising. Additional development effort is needed and will be very worthwhile.

ADDITIONAL SOFTWARE DEVELOPMENTS WANTED FOR MODELING AND CONTROL OF FLEXIBLE SPACE SYSTEMS

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WORKSHOP ON COMPUTATIONAL ASPECTS IN THE CONTROL OF FLEXIBLE SYSTEMS
JULY 12-14, 1988
WILLIAMSBURG, VIRGINIA

ADDITIONAL SOFTWARE DEVELOPMENTS **URGENTLY** WANTED

- ACCURACY-PRESERVING COMPUTATIONALLY EFFICIENT COORDINATE REDUCTION OF FINITE-ELEMENT MODELS,

  TO ENABLE

  1. PRE-DESIGN OPEN-LOOP DYNAMIC ANALYSIS OF **REALISTIC, LARGE,** FLEXIBLE SPACE STRUCTURES

  AND

  2. POST-DESIGN **FULL-ORDER CLOSED-LOOP** EVALUATION OF CONTROL SYSTEMS FOR SUCH STRUCTURES

- ANALYTICAL SELECTION OF CONTROL AND STATE WEIGHTS,

  TO AID

  DESIGN OF LINEAR-QUADRATIC REGULATORS DESIRED FOR VIBRATION CONTROL OF FLEXIBLE SPACE STRUCTURES

ACCURACY-PRESERVING COMPUTATIONALLY EFFICIENT COORDINATE REDUCTION OF FINITE-ELEMENT MODELS

DESIGN OF RELIABLE CONTROL SYSTEMS FOR FLEXIBLE SPACE SYSTEMS

NEEDS

1. CAREFUL PRE-DESIGN OPEN-LOOP DYNAMIC ANALYSIS OF THE SPACE STRUCTURE, AND

2. CAREFUL POST-DESIGN FULL-ORDER CLOSED-LOOP EVALUATION OF CONTROL SYSTEMS FOR THE STRUCTURE

NEEDS PRE-DESIGN OPEN-LOOP DYNAMIC ANALYSIS

-- TO ASSESS EFFECTS OF DISTURBANCES ON SYSTEM PERFORMANCE, E.G., POINTING STABILITY, LINE-OF-SIGHT ERRORS, ...

-- TO IDENTIFY STRUCTURAL MODES NEEDING ACTIVE CONTROL

-- TO FORM A COMPUTATIONALLY FEASIBLE REDUCED-ORDER CONTROL-DESIGN MODEL

-- TO ASSSESS EFFECTIVENESS OF CONTROL ACTUATORS AND SENSORS

NEEDS POST-DESIGN FULL-ORDER CLOSED-LOOP EVALUATION

-- TO DETECT POSSIBLE INSTABILITY INTRODUCED BY REDUCED-ORDER CONTROL DESIGN

-- TO VERIFY ACTUAL TIME-DOMAIN PERFORMANCE

-- TO TEST ROBUSTNESS TO MODELING ERRORS, PARAMETER VARIATIONS,...

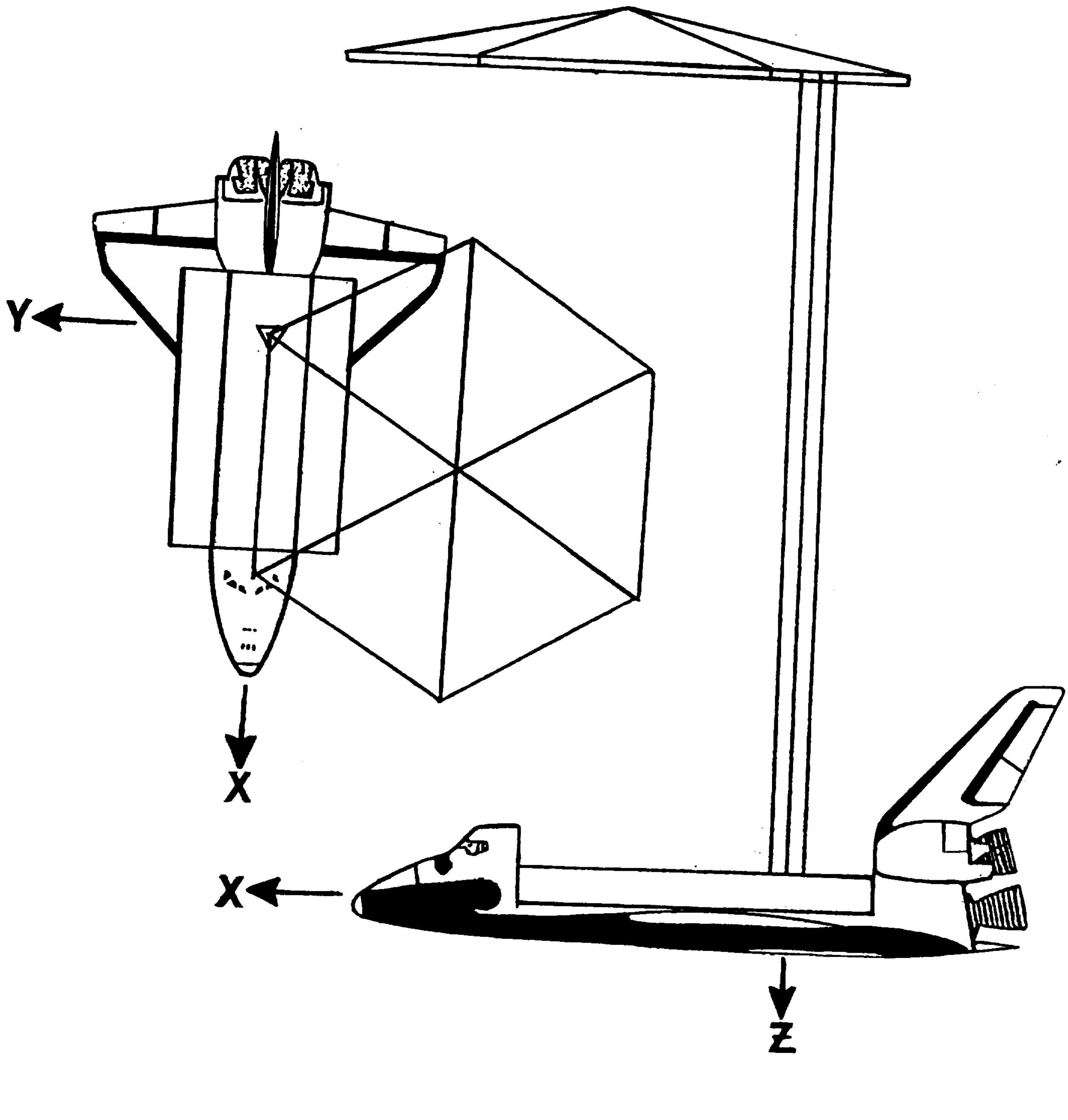

Fig. 1-1 Spacecraft Control Laboratory Experiment (SCOLE)--
the orbital Shuttle-Mast-Antenna configuration.

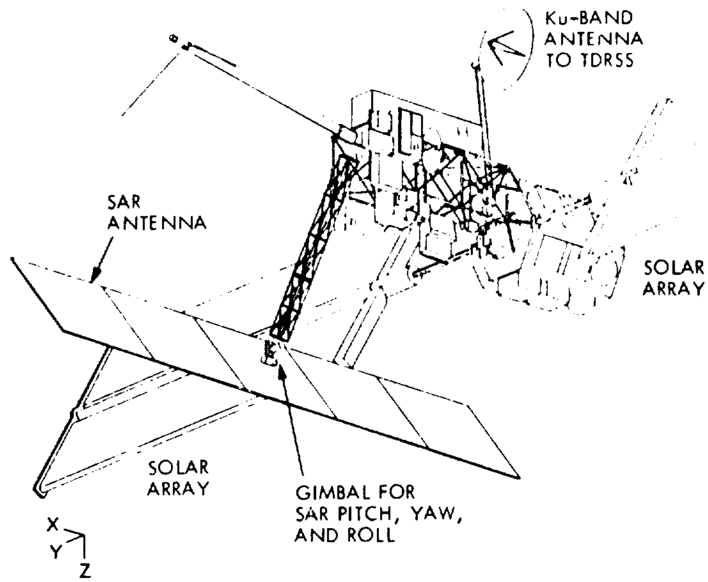

Figure 1. A Possible Eos Polar Platform Configuration

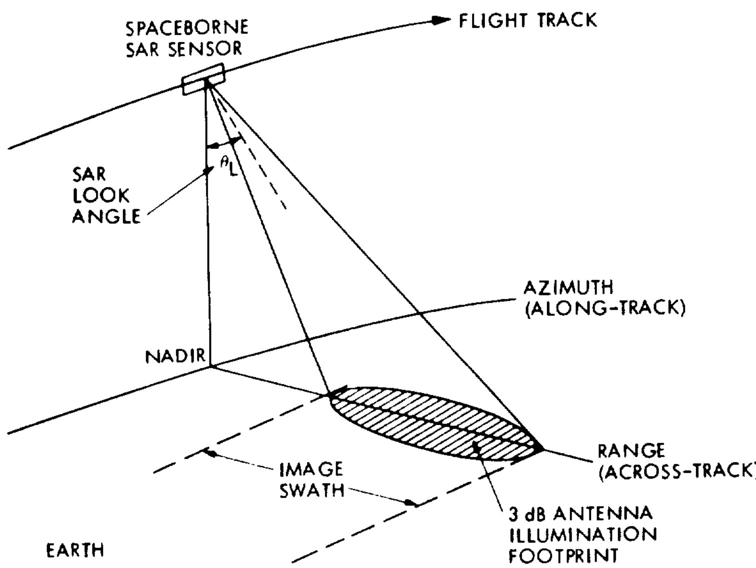

Figure 2. SAR Imaging Geometry

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AIAA-87-0022 PAPER:
"EARTH OBSERVING SYSTEM INSTRUMENT POINTING CONTROL MODELING FOR POLAR ORBITING PLATFORM,"
BY H.C. BRIGGS, T.KIA, S.A. MCCABE, AND C.E. BELL

- NASTRAN STRUCTURAL DYNAMICS MODEL OF PLATFORM: 200 NODES
  - -- 600 TO 1,200 DOFS
  - -- 40 MODES BELOW 10 HZ

- SLEW OF SAR ANTENNA ABOUT ITS BOOM AXIS WAS SIMULATED
  - -- TO ASSESS THE POINTING CONTROL AND STABILITY OF INSTRUMENTS MOUNTED ON THE CARRIER STRUCTURE DURING SLEWING OF ADJACENT INSTRUMENTS.

- "LARGE ANGLE TIME-DOMAIN SIMULATIONS CAN PRESENTLY BE CONDUCTED USING DISCOS, BUT DUE TO EXECUTION EXPENSE AND THE DIFFICULTY OF USER INTERFACE THIS APPROACH IS IMPRACTICAL FOR EOS STUDIES.

NEXT GENERATION SIMULATION TOOLS WHICH REDUCE THE NUMBER OF NUMERICAL OPERATIONS FROM ORDER N^4 (DISCOS) TO N^3 (TREETOPS) AND BEYOND TO ORDER N ARE URGENTLY NEEDED TO EFFICIENTLY AND COST EFFECTIVELY VERIFY THE PERFORMANCE OF LARGE SYSTEMS OF MULTIPLE ARTICULATED AND ROTATING ELEMENTS SUCH AS EOS PLATFORMS."

SOME SERIOUS TECHNICAL PROBLEMS

CURRENT REDUCED-ORDER MODELS ARE GENERALLY NOT APPROPRIATE FOR REALISTIC, LARGE, FLEXIBLE SPACE STRUCTURES:

- MODEL ACCURACY VS COMPUTATIONAL CAPABILITY

  IF COMPUTATIONALLY FEASIBLE TO SIMULATE ON THE COMPUTER, THEN
  LIKELY NOT ACCURATE ENOUGH TO REPRESENT THE FLEXIBLE STRUCTURE;

  IF SATISFACTORILY ACCURATE, THEN
  MOSTLY TOO LARGE FOR EFFECTIVE DYNAMIC SIMULATION ON COMPUTER

- COMPUTATIONAL EXPENSE AND ACCUMULATED ERRORS

  COMPUTING A VERY LARGE NUMBER OF NORMAL MODES IS VERY EXPENSIVE;

  ACCUMULATED COMPUTATIONAL ERRORS IN THE NATURAL FREQUENCIES AND MODE SHAPES GROW VERY RAPIDLY.

- WASTED EXPENSIVE MODAL COMPUTATIONS

  MANY USELESS MODES COMPUTED,
  THEN IGNORED IN CONTROL DESIGN OR EVALUATION

  -- UN-RELATED TO DISTURBANCES CONCERNED,
  OR CONTROL ACTUATIONS CONSIDERED

- ACCURACY-SACRIFICING COORDINATE REDUCTION

  POPULAR GUYAN REDUCTION TECHNIQUE IS OFTEN USED FIRST
  TO REDUCE THE LARGE FINITE-ELEMENT STIFFNESS AND MASS MATRICES

  -- LARGE ERRORS INTRODUCED THEREBY;
  INCREASE AS THE **SQUARE** OF FREQUENCIES OR HIGHER

INNOVATIVE RAYLEIGH-RITZ METHOD

- A TREND TOWARDS SOME INNOVATIVE USE OF NON-MORMAL MODES (SUCH AS RITZ OR LANCZOS VECTORS) FOR REPRESENTING THE STRUCTURES BY A MUCH SMALLER NUMBER OF GENERALIZED COORDINATES

-- AVAILABLE RESULTS INTERESTING AND PROMISING.

-- ADDITIONAL DEVELOPMENT AND EXTENTION EFFORTS NEEDED.

- RAYLEIGH-RITZ METHOD

-- ASSUMED SHAPES: $Q_1, Q_2, \ldots, Q_N$ (SMALL N)

-- APPROXIMATE THE STRUCTURAL DISPLACEMENT VECTOR X:

$$X = Z_1 Q_1 + Z_2 Q_2 \ldots + Z_N Q_N = Q Z$$

$$Q = \left[Q_1, Q_2, \ldots, Q_N\right], \qquad Z = (Z_1, Z_2, \ldots, Z_N)$$

-- REDUCE ORIGINAL FINITE-ELEMENT MODEL: $M \dfrac{D^2X}{DT^2} + K X = F(T)$

TO

$$\boxed{(Q^T M Q) \frac{D^2Z}{DT^2} + (Q^T K Q) Z = Q^T F(T)}$$

-- ORIGINAL LARGE MATRICES M AND K NOW REDUCED TO SMALLER ONES:

$$M_C = Q^T M Q, \qquad K_C = Q^T K Q$$

- WILSON-YUAN-DICKENS ALGORITHM

-- ASSUME $F(T) = B\, U(T)$, $U(T)$ = A SCALAR FUNCTION

-- GENERATE AND ORTHOGONALIZE THE ASSUMED SHAPES SEQUENTIALLY:

$$K Q_1^* = B \Longrightarrow Q_1$$

$$K Q_2^* = M Q_1 \Longrightarrow Q_2$$

$$\cdots\cdots$$

$$K Q_N^* = M Q_{N-1} \Longrightarrow Q_N$$

ADDITIONAL DEVELOPMENT AND EXTENTION EFFORTS WANTED

- COMPUTATIONAL PROBLEMS WITH ORTHOGONALIZATION

1. ACCUMULATED ROUNDOFF ERRORS CAN DESTROY THE ORTHOGONALITY OF THE RITZ VECTORS THUS GENERATED

-- NEED TO RE-ORTHOGONALIZE WHENEVER ORTHOGONALITY IS LOST

2. COMPUTATIONAL INTENSIVE: PERFORM GRAM-SCHMIDT ORTHOGONALIZATION EVERY TIME A VECTOR Q_I^* IS GEANERATED

-- NOUR-OMID AND CLOUGH'S SOLUTION WAS TO ORTHOGONALIZE ONLY WITH RESPECT TO TWO PREVIOUS VECTORS.

-- THE MOST TROUBLESOME DRAWBACK OF THE LANCZOS ALGORITHM REAPPEAR:
EASY LOSS OF ORTHOGONALITY OF THE LANCZOS VECTORS;
RE-ORTHOGONALIZATION REQUIRED WHEN ORTHOGONALITY IS LOST

- EXTENSION BEYOND THE SPECIAL CASE OF SCALAR FORCES

-- THE WILSON-YUAN-DICKENS ALGORITHM WAS FORMULATED FOR SCALAR FORCES;
NOT DIRECTLY APPLICABLE TO THE GENERAL CASE OF MULTIPLE SIMULTANEOUS DISTURBANCE (OR CONTROL) FORCES

-- SO WAS NOUR-OMID AND CLOUGH'S VERSION USING LANCZOS VECTORS

-- BUT, SPACE SYSTEMS LIKELY BE SUBJECT TO MULTIPLE DISTURBANCES NOT ONE AT A TIME, BUT SIMULTANEOUSLY

-- ALSO MOST CONTROL SYSTEMS USE MULTIPLE INDEPENDENT ACTUATORS TO APPLY FORCES/TORQUES TO THE STRUCTURES SIMULTANEOUSLY.

LINEAR-QUADRATIC REGULATORS (LQR) FOR FLEXIBLE SPACE STRUCTURES

- TRUNCATED MODAL MODEL OF THE FLEXIBLE STRUCTURE

$$\ddot{\eta}_i + 2\zeta_i \omega_i \dot{\eta}_i + \omega_i^2 \eta_i = \phi_i^T B_F u \qquad i = 1, \ldots, N$$

- PUTTING INTO STATE-SPACE FORM

$$\dot{x} = A x + B u$$

WITH $x = \begin{bmatrix} \eta \\ \dot{\eta} \end{bmatrix} \qquad \eta = \begin{bmatrix} \eta_1 \\ \eta_2 \\ \vdots \\ \eta_N \end{bmatrix}$

- LQR DESIGN:

FIND A FEEDBACK GAIN MATRIX K SUCH THAT

$$J = \int_0^\infty (x^T Q x + u^T R u)\, dt$$

IS MINIMIZED WITH $u = K x$

- GIVEN THE CONTROL AND STATE WEIGHTING MATRICES R AND Q, ANY "MODERN CONTROL" DESIGN PROGRAM, SUCH ORACLS, CTRL-C, CAN PRODUCE AN OPTIMAL SOLUTION K VIRTUALLY AUTOMATICALLY

DESIGN OF LINEAR-QUDRATIC REGULATORS FOR ACTIVE AUGMENTATION OF SPECIFIIED DAMPING TO SPECIFIC MODES

APPRAOACH 1. CONSTRAINED OPTIMIZATION

OPTIMIZE THE PERFORMANCE INDEX J WITH THE SPECIFIED DAMPING RATIOS AS CONSTRAINTS.

-- CONSTRAINED OPTIMIZATION IS PARTICULARLY COMPLICATED WHEN DYNAMIC EQUATIONS ARE INVOLVED

APPROACH 2. ALPHA-SHIFT

SHIFT ALL POLES TO THE LEFT OF THE IMAGINERY AXIS BY A CONSTANT α.

-- SOME MODES MAY NOT GET ENOUGH DAMPING TO BE CLOSE TO THE SPECIFIED, WHILE SOME OTHERS MAY GET TOO MUCH MORE THAN THE SPECIFIED.

APPROACH 3. TRIAL AND ERROR ON THE CONTROL AND STATE WEIGHTS

START WITH DIAGONAL R AND Q WITH SOME ARBITRARY NUMBERS, E.G., 1;
CARRY OUT THE DESIGN OF THE CORRESPONDING LQR;
EVALUATE THE CLOSD-LOOP POLES, AND HENCE THE DAMPING RATIOS.

TRY OTHER CONTROL AND STATE WEIGHTS,
REPEAT THE DESIGN-EVALUATION CYCLE,
UNTILL THE RESULTS ARE SATISFACTORY.

-- THE CONTROL AND STATE WEIGHTS USED MOSTLY ARE AD HOC;
THE TRIAL-AND-ERROR PROCESS IS MOSTLY ENDLESS,
VERY TIME CONSUMING

ADDITIONAL SOFTWARE DEVELOPMENT WANTED

SOFTWARE MODULES FOR AIDING DESIGNERS IN MAKING GOOD INITIAL CHOICES,
AND INTERMEDIATE ADJUSTMENTS, OF THE CONTROL AND STATE WEIGHTS

SO THAT,

THE RESULTING DESIGN OF LINEAR-QUADRATIC REGULATORS
CAN, WITHIN ONLY A FEW ITERATIONS, SATISFY CLOSELY
THE DESIGN SPECIFICATIONS,
E.G., ON DAMPING AUGMENTATION, STIFFNESS AUGMENTATION,
LINE-OF-SIGHT POINTING ACCURACY, ETC.

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SESSION II - SURVEY OF AVAILABLE SOFTWARE

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