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MULTI-AXIS MANUAL CONTROLLERS

A STATE-OF-THE ART REPORT

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INTRODUCTION

Flight controls have been the subject of many studies and the interaction between pilot and controls is well documented. Typically, conventional flight controls of the joystick or wheel and column type are connected directly, or with power assist, to specific control surfaces or devices and control the movements of the vehicle. Control systems have evolved to reduce the physical effort of piloting and to generate tactile feedback signals by presenting control loading forces to the pilot's hand. This feedback is an essential factor for stability in the pilot-vehicle system and a major component of the dynamic man-machine interface.

Fly-by-wire and fly-by-computer technology have eliminated the need for direct linkage to the flight surfaces and have given rise to the concept of direct flight path control and maneuver-oriented pilot inputs. The sidearm controller was one of the first devices to emerge, reflecting the need of the cockpit designer for freedom to locate the primary flight controls away from the center of the cockpit. This need is even greater in spacecraft where the contour-seated astronaut presents special difficulties in terms of manual access to and operating envelope of primary flight controls. Furthermore, spacecraft flight demands independent control in all six degrees of freedom as well as simultaneous commands in two or more. Remote manipulators, still another newly developing technology, have similar command requirements.

PURPOSE AND SCOPE OF SEARCH

A literature search was carried out as part of a study to examine the feasibility of a six degree of freedom hand controller. A review of current work in the area of multi-axis controllers was achieved by visits to relevant research and design centres. The focus of the search was specific; however, included related areas, approaches to manual control, applications of manual controllers and selected studies of the human neuro-muscular system.

Earlier, similar efforts by the authors failed to disclose a reliable single source of information covering the field of multi-axis control devices. Furthermore, no specific titles or sections dedicated to manual control seem to exist in any of the listings and abstract journals checked.

METHODS OF SEARCH

The criteria defined for hand controller functions and related topics were transformed into descriptors recognizable by librarians and information systems. The descriptors were further adjusted as each library or service made recommendations as to the exact words to be used in defining the areas of the search.

Both direct search methods and computerized information retrieval were used. Direct search was carried out in specialized libraries, such as the Aeronautical Library of the National Research Council of Canada, Ottawa, and the technical library of the Ecole Polytechnique in Montreal. Computer searches were requested in these libraries and those of McGill and Concordia Universities of Montreal, in addition to a manual search. Abstracting services and journals were also scanned for reference and for evidence of trends or new activities in the manual control field. Manual search produced a "hit rate" of nearly 100%, computer searches 30%, abstract journals approximately 65%.

In terms of completeness, the authors are confident that the bulk of significant work in the area of multi-axis manual controllers in North America has been included, except for one important manufacturer whose disclosures are conspicuously absent. In addition, during the state of the art survey, researchers in the field were asked for references.

ANALYSIS OF RESULTS

The net results of this search turned out to be very similar to those of a 1972 search, both in volume and in content. There is a lot of interest in the general area but very few determined efforts to define a design philosophy for multi-axis controllers or to test these under representative conditions. In sharp contrast is the consistently active and well-reported research area of describing and modelling the human operator in continuous control systems. By far, the most appropriate and comprehensive activity is the ongoing research project at JPL, led by Dr.Bejczy.

Manual controller design and evaluation is usually included, as a minor task, in the development of vehicle handling characteristics. The reports dedicate much space to system aspects, but deal with the controller in a paragraph or two. In the absence of a definitive design philosophy, the best source of information would be pilot opinion and performance/preference ratings derived from full flight simulation or actual flight evaluation. However, such reports are few.

Theoretical studies of man-in-loop requirements and reports on laboratory-based experiments are more plentiful and some were found to contain useful design data. However, in general, the studies are limited to one or two degrees of freedom, and test conditions are less than representative. Frequently, results are arbitrarily extrapolated to the real world. Such conclusions must be accepted with due qualification and great caution. Developments in fields related to controller design and incidental studies show a significant increase since 1970-72.

No final answers have been found in the literature to some fundamental questions related to multi-axis manual control. Others have been investigated in part only, hence the answers are only partially valid and reliable.

Are six degrees of freedom too many to control with one arm and hand? No proof is offered, affirmative or negative. Qualitatively, the needs and requirements are well understood; the control task must become a means of accomplishing objectives, not to be a task in itself. Bejczy says the controller should be transparent to its operator, it should not in any way restrict the input commands except as dictated by a scheduled force feel system reflecting the controller system conditions to the operator.

Do mechanical properties and stick feel affect pilot/system performance? The affirmative and unequivocal statement by Kruger is supported by a large body of reports on research and development work on joysticks, grip shapes, sidearm and center stick configurations, stick forces, breakouts and gradients, ranges of motion, damping and other characteristics. The necessity and usefulness of proprioceptive feedback is accepted, but there is wide disagreement as to the nature, pattern and balance (harmony) of stick forces to be used. This, is partially due to the individual requirement of each manually controlled system and each control task.

The controller should be transparent in that the operator should feel that he is achieving the task, not merely moving a joy stick or control. This transparency is enhanced if there is a spatial correspondence between the controller and task, enabling the pilot or operator to predict the results of his manual inputs at all times with an absolute minimum of mental effort or added workload.

The isometric or force stick offers engineering advantages and reappears in the literature frequently, as a means of mechanizing the side-arm controller. Its proponents claim that since force is the principal parameter of proprioception, and since pilot comments are mostly centered on stick forces vs system response, deflection is not necessary for aircraft controls. Many of such statements are based on laboratory experiments with non-representative equipment. Some claim definite superiority for pressure (force) controls, especially with increasing task complexity. Flight tests with isometric sticks have been disappointing, but this is blamed on lack of proper understanding and application of this type of controller. A tendency to generate crosstalk between axes, poor stick feel and hand fatigue are reported most often ad drawbacks or areas of further work to be done. In summary, the superiority of isometric sticks for spacecraft application is by no means proven.

Forces appearing on the control stick, both active and reactive (resisting movement) have been the focus of interest since the early days of systematic flight control design. The principal concern is the prevention of overcontrol or overstressing the vehicle. Since stick force dynamically leads stick deflection, stick forces provide a predictive capability similar to quickening of displays and promote head-up piloting. Even passive force systems can generate a "solid feel" which spells pilot acceptance and positive stability, while negative stick stability, backlash and Coulomb friction degrade control accuracy and increase pilot workload.

How Does the Controller Fit into the Man-Machine System? The picture is by no means complete but several research efforts and trends were identified, e.g. the concept of inner/outer control loops, objective measurement of workload, and the concept of the internal model. Typically, pilot workload levels have been derived from debriefing questionnaires and pilot rating of system controllability. A more objective result can be objective result can be obtained by measuring the direct and indirect muscular effort extracted from the pilot by electromyography (EMG) and by counting the control reversals (frequency of inputs) during the time frame of a given task. "White knuckles", or unproductive nervous effort is proposed as a measure of workload stress, and EMG power spectra as a metric of local muscle fatigue, both related to controller characteristics and forces. A flight evaluation related stick sensitivity, lack of command/display harmony or cross coupling tendencies to control reversals and hence workload.

The concept of an internal normative model is relatively new, although its equivalent (body image) has been recognized in pschology and physical medicine for quite some time. The human acquires through experience and cognitive process a fast-running model of the system response he is trying to bring about. If the system fails to match this model, he either increases his workload or registers a system failure. Attempts are being made to quantify this model and relate it to tracking tasks.

Is Six-Axis Control Necessary? Whitsett says yes, prompted by MMU experience in Skylab. It may also safely be said that the control-configured aircraft and direct flight path control will eventually require command inputs in six degrees of freedom. Alternatives are tried, such as 2 x 3 degrees of freedom and foot controls. The former occupies both hands and continuous control is interrupted every time an additional manual activity is required such as adjustment of TV cameras. Foot contrrl is generally slow, and inaccurate as shown by the Skylab experience.

Integrated controls are advocated for U.S. Army helicopters where a wounded pilot could save his crew if he could fly the helicopter with a single hand.

Is a Six-Axis Device Feasible? The literature is inconslusive. The State-of-the-Art survey found three models, and several four DOF devices. No definitive design philosophy could be found on such topics as the cascading order of axes, or the segments of the arm and hand to be used as command sources.

In terms of existing designs, several six degree of freedom controllers have been found.

a) An isometric six axis controller developed at MIT and evaluated at Marshall Space Centre, Problems have been encountered due to cross-coupling and operator fatigue.

b) A controller developed by Stark Draper Labs which includes three rotational displacement axes and three isometric force axes.

c) A six axis, floor mounted displacement unit used at Martin Marietta in conjunction with Manned Manoeuvering Unit studies.

d) An experimental six degree of freedom research tool currently in use at JPL.

e) A hard suit replica controller evaluated at NASA/AMES and at JPL.

CONCLUSIONS AND RECOMMENDATIONS

The search has been productive in terms of generating a data bank, and supporting the development of a six-axis controller model. However, gathering information in this specialized field is still a labourious process with unpredictable results. The authors appeal to the Annual Conference on Manual Control to act as a forum of information exchange, to establish descriptors and abstracting methodology to show the correct interest profile for publications and to generally promote information exchange. CAE Electronics in Montreal has a computerized data base on man-machine systems which could be expanded to the benefit of all.