APPLICATION OF AN INTERACTIVE GRAPHICS SYSTEM TO THE KINEMATIC DESIGN OF AN ARTIFICIAL KNEE JOINT

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KINSYN is an interactive general purpose computer system for the kinematic synthesis and analysis of mechanisms. It is applicable to kinematics problems ranging from the synthesis of spacecraft antenna deployment mechanisms to the design of folding high chairs. Features of KINSYN have been described in several recent publications [1,2,3].

Interactive computer-aided design systems have a tremendous untapped potential for aiding in the solution of bioengineering problems. Spatial relationships, such as the structural features of the human body, their interconnections and the changes in their relative positions during an interval of time, can be readily studied on a computer with the aid of interactive computer graphics. Curve scanners and analog tracing devices make possible direct digitization of x-ray and other two or three dimensional data. Graphical displays, plotters, and numerically controlled machines make possible direct output of spatial information. The effective range of such techniques could be further amplified through the use of remote graphics terminals and centralized computing facilities. In this way it can become economically feasible to custom tailor orthopedic devices to the needs of an individual patient.

As has already been indicated KINSYN is a general purpose system for kinematic synthesis and analysis and not primarily a vehicle for orthopedic studies. Our curiosity was aroused as to the possible utility of the KINSYN system in the design of prosthetic devices. The system was then used to explore knee joint kinematics. As is well known, the kinematics of a normal human knee joint are highly complex and only a few days could be devoted to this work which was peripheral to our main research effort on linkage kinematics. However, it sufficed to show that KINSYN could be a powerful tool for use in the design of polycentric knee mechanisms, either for orthotic braces or for above the knee prostheses.

The results shown in this paper were obtained during the first two or three trial runs on KINSYN. Of course, extensive work would remain to be done in order to apply these techniques to a practical artificial limb design. Nonetheless, the fact that so much useful design data can be obtained so readily with the aid of KINSYN indicates that it could be a significant aid in a physiological limb development program.

First, let us briefly review the nature of the motion encountered in a knee joint. Typical artificial limbs and orthotic knee braces make the simplifying assumption that the motion is a simple rotation of the leg with respect to the thigh. In actual fact, articulation of the femur with respect to the tibia does not take place about a single pivot fixed with respect to the two members. Rather, the position of the instantaneous axis of rotation depends on the degree of flexion of the limb. The relative motion is not evan planar, but is "pseudo-planar." During most of the motion, the leg swings in what is essentially planar motion, but as the knee joint approaches extension there is a "screwing home" or a spatial rotation of the tibia with respect to the femur.

These complex motions arise from interactions of the condyle surfaces and the various ligaments.* When the leg is fully flexed, the posterior surfaces of the femoral condyles roll without slipping on the meniscotibial surfaces. As the posterior two-thirds of the two femoral condyles are geometrically similar and parallel, the motion is essentially planar. The instant center of rotation passes through the points of rolling contact for the two femoral condyles. As the leg starts to extend, this instantaneous axis of rotation shifts anteriorly along the condyles, sweeping out two ruled spatial surfaces known as axodes. One axode is fixed with respect to the femur and the other is rigidly attached to the moving tibia. As the fully flexed leg starts to extend, the corresponding portion of the femoral axode is essentially a simply curved ruled surface tangent to the femoral condyles.

As the leg extends, a gliding motion is superimposed upon the simple rolling of the condyles. As a result, the instantaneous axis of rotation leaves the surface of the condyles, moving anteriorly and in a superior direction so that it passes through the femur. The motion is still nearly planar, with both the medial and lateral portions of the joint shifting anteriorly equally.

Finally, the lateral condyle of the femur is snubbed by the tightening of the anterior cruciate ligament. It is pulled anteriorly and medialward as it comes to a stop. Meanwhile, the medial condyle is pulled posteriorly and medially by the continued muscular action. The net result is to rotate the thigh internally with respect to the leg.

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* The following kinematic description is based upon the anatomical information found in Ref. 4.

In the position of full extension, the joint is locked by the accurate meeting of the condyles and their corresponding meniscal and tibial surfaces and by the meshing of the anterior cruciate ligament with the intercondylar fossa of the femur. As the joint "screws home," the instantaneous rotation axis of the leg shifts away from the horizontal. Thus, the knee joint is really a spatial joint, only approximately modeled by a planar hinge.

The exact spatial motion of the joint could be exactly replicated by rolling of the femoral and tibial axodes on one another, with a limited amount of slipping permitted only in the direction of their common tangent line. A slightly cruder model of the knee motion would ignore this small component of slip in the direction of the instantaneous axis. If one is willing to ignore the terminal spatial rotation of the leg as it reaches full extension, then one could consider the axodes as simply curved surfaces (in two dimensions, as "polodes") and model the motion as pure planar rolling of one axode on the other. Finally, at the crudest level of approximation, one could consider the motion as a simple rotation of the tibia with respect to the femur.

Many classes of mechanisms can approximate the motion of the femur with respect to the tibia. For incorporation into a practical artificial limb, however, a mechanism must be simple, inexpensive, and reliable. These considerations are more important than exact replication of the normal knee motion.

An important class of mechanisms that can closely match the planar motion of an actual knee joint is the class of pin or slider-jointed plane mechanisms. The simplest such mechanisms are the four-bar linkage and the slider-crank mechanism. Four-bar linkages have, in the past, been used in polycentric knee joint designs. However, the design of such mechanisms has been a laborious task of trial and error, resulting in a single mechanism design which roughly approximates the desired motion.

With the aid of KINSYN, it is possible to feed dimensionally exact radiograph data for a particular patient's knee motion into the computer. X-ray data can be taken at four angles of knee flexion, digitized, and entered into the machine. Within a few seconds, the computer then displays two curves, superimposed on the picture of the femur and the tibia in the four design or "precision" positions. These curves, so called "Burmester curves," represent the loci of all theoretically possible pivot points for linkages which will be capable of exactly replicating the desired knee motion at the specified design positions.*

For four specified design positions, there is theoretically a double infinity of four-bar linkages which will be capable of exactly reproducing the desired motion. With the aid of the KINSYN system, the orthopedic limb designer could see the locus of all of the mechanism possibilities displayed for his selection on the screen. He can instantly weed out unfruitful designs, because it is obvious from looking at the loci of possibilities that many involve pivots that do not fall conveniently close to the femur or tibia. It is possible for the designer to sweep a selection cursor along the curves in a continuous fashion. As he does so, flashing legends continually assess the acceptability of the instantaneously displayed alternative, but the ultimate decision is made by the human based, not only upon the flashing messages displayed on the screen, but also upon his subjective consideration of the subtle factors which must be taken into account in the design of an artificial knee joint.

Incidentally, the computer displays not only the possible four-bar linkages that will exactly reproduce the four design positions of the knee, but, at the same time, it shows the possibilities for slider-crank and turning-block mechanisms that will precisely move the leg through the design positions with respect to the femur. Slider-crank or turning-block mechanisms for the task of guiding the femur relative to the tibia would have a doubly pinned link pinned at one end of the femur and at the other end to the tibia. In addition, they would have a slider pinned to either the femur or tibia and sliding in straight guides with respect to the other bone. Whether one considers the mechanism a slider-crank mechanism or a turning-block mechanism depends on one's point of reference, whether the fixed "framework" is considered to be the femur or the tibia. Kinematically, the two mechanisms are inversions of one another. In theory, one can design a single infinity of turning-block mechanisms and a single infinity of slider-crank mechanisms, any of which would be capable of exactly reproducing the specified four design positions. These possibilities are also displayed by KINSYN for the designer, as they involve special choices of pivot locations from the already displayed Burmester curves. Thus, instead of a laborious random trial and error design process that will result in only a limited number of mechanisms which crudely approximate the exact knee motion, this computer graphics approach rapidly yields an infinite selection of possibilities, any one of which is theoretically capable of exactly generating the desired motion at the four design positions. Certain of these mechanisms are unacceptable for other structural reasons, but those designs are automatically flagged by the computer by means of the flashing legends.

Once the designer has tentatively selected a knee joint mechanism from the displayed alternatives, he can animate it on the display screen and study the motion of the leg at intermediate locations between the design positions. When using pinned linkage mechanisms of this type, it is theoretically impossible to exactly match a continuous motion such as that of the knee joint over its entire range of motion. However, by matching the motion exactly at four design positions, say when fully extended and at three flexed positions, one can attain a design that will come very close to exactly matching the motion over its entire range. At any rate, the resulting design will probably be far superior to one which resulted from trial and error and which matches the exact motion at only one or two positions.

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* For generality, this discussion will talk about producing motion of the femur with respect to the tibia, rather than concerning itself with the details of whether the particular application is to an orthotic brace or an artificial limb. The femur and tibia are considered as infinite bodies having a desired motion with respect to one another, regardless of the mechanical details of how that motion comes about.

Once computer facilities for this task were set up, custom brace or limb designs could be generated for only a few dollars worth of computer time. Output of the system could be either in terms of specific adjustments that could be made to a standardized adjustable limb or brace, or the output could be in terms of a control tape for a numerically controlled machine tool which could, in turn, custom produce a large number of prosthetic devices in a single run. In either case, the patient could have a custom fitted polycentric brace designed to his exact requirements at a cost perhaps lower than that of a conventional hand fitted prosthesis.

Still another form of output possible from such a system might be in the form of an atlas or table of adjustments for artificial limbs. That is, a wide range of data taken from knee x-rays could be fed into the computer, and an atlas of knee mechanisms could be generated. Orthopedic shops could then closely fit most of the patient population with knee joints by matching their data with that in the atlas and reading off the appropriate adjustment dimensions to best fit the patient. The fitting regimen could then consist of insertion of standardized shims or setting to predetermined adjustments based upon this table of values.

The first beneficial results from such a computer study would be in making possible the rapid evaluation of a wide range of alternative concepts for artificial joint designs. Generally desirable characteristics for an artificial knee joint could be rapidly explored in detail with the aid of computer graphics and systematic synthesis procedures. Flexibility in choosing the input design positions could make it possible to vary the nature of the solutions obtained. For example, if desired, a designer could readily incorporate hyperextension locking into a knee joint by proper choice of pivot locations on the Burmester design curves. In this way, he could insure that the weight bearing line fell anterior to the instantaneous axis of the joint. The ability to introduce artificially a design motion differing from that encountered in a normal knee would make it possible to insure stability of the knee joint by producing maximum elevation at a point prior to full extension.

Our exploration of slider mechanisms for knees resulted in a natural fashion from the built in capabilities of the KINSYN system. However, it is felt that this is a valuable area for further research and one heretofore unexplored. There is a possibility that a slider element in a knee joint could be adapted to serve a double function: first, it could serve as a basic part of the joint, producing the inherent motion of the femur relative to the tibia. Secondly, it could be part of a modulated dashpot mechanism, providing swing and stance control.

As pointed out in reference 5, physiological knee mechanisms provide a number of inherent advantages over single pivot limbs. In the case of an orthotic brace, a polycentric knee can closely match the actual knee motion, thereby avoiding joint wear and trauma due to misalignment of the instant center of the real limb and the brace. [6] In either the case of an orthotic brace or of an artificial limb, a polycentric knee makes flexion easier. There is a rapid shift of the instant center forward of the weight bearing line. This permits the vertical force to aid in further flexing of the knee. Due to the shifting position of the instantaneous rotation axis, stable locking of the joint can be attained without the need for hyperextension. Having the instant center move upwards means that the loading required from the stump is lowered both for maintaining stability and also for starting flexion of the leg. Finally, a dynamic advantage of a polycentric limb is that, since its axis location closely matches that of the normal limb, it can be made to have a period closely approaching that of a normal limb. This also results in a good gait appearance.

Based upon conclusions drawn from only a few days of exploration of knee joints using KINSYN, it appears to be a tremendously promising tool for further study in this field. Unfortunately, due to other requirements on our time and resources, we were not able to carry this preliminary investigation any further. However, it was felt that the results which we had obtained were significant, in part because of the facility with which they were obtained and also because of their implications as to the future possibilities for interactive computer graphics in orthopedic and bioengineering studies.

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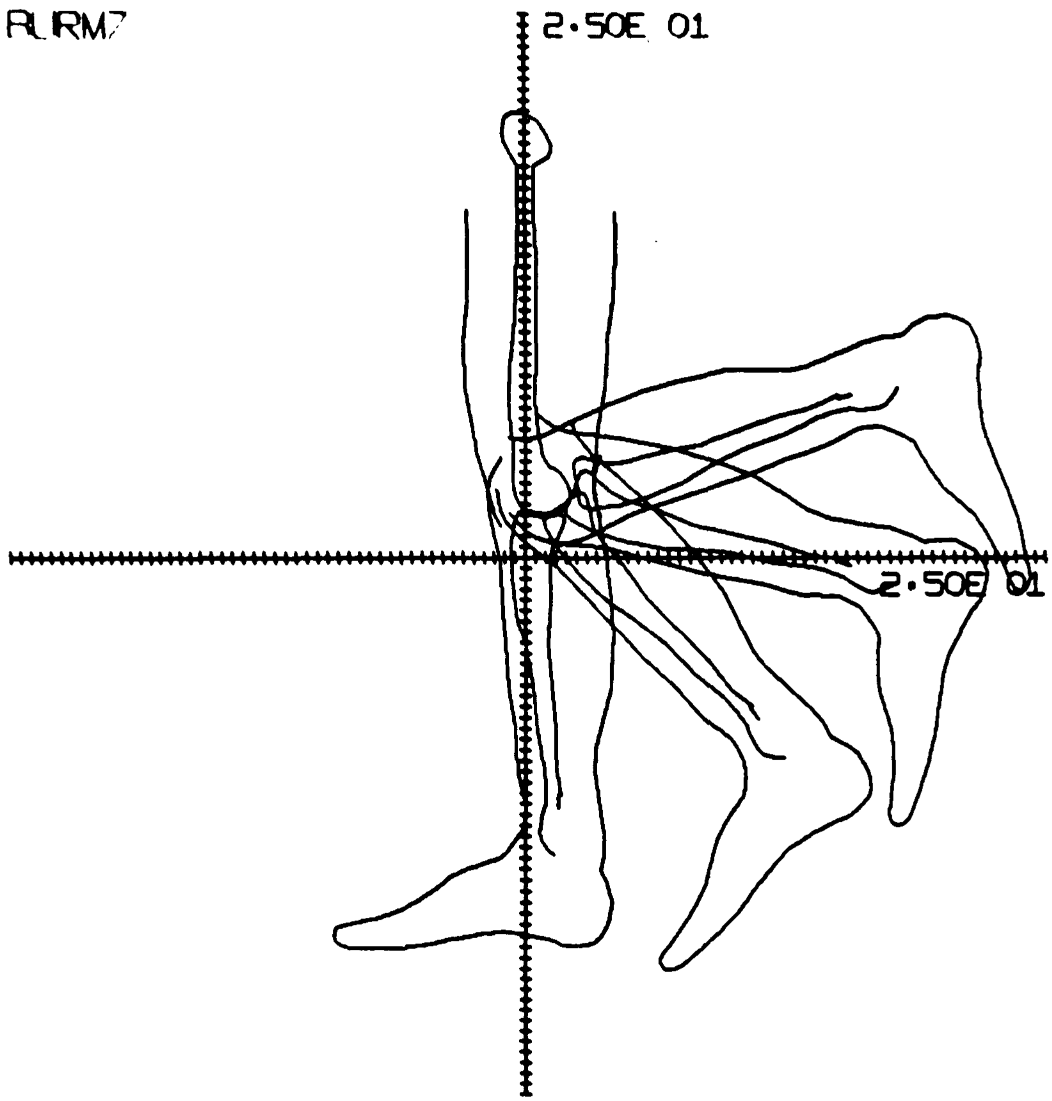

Figure 1: KINSYN scope display of input data for normal knee motion. Synthesized mechanism is to exactly match these design positions.

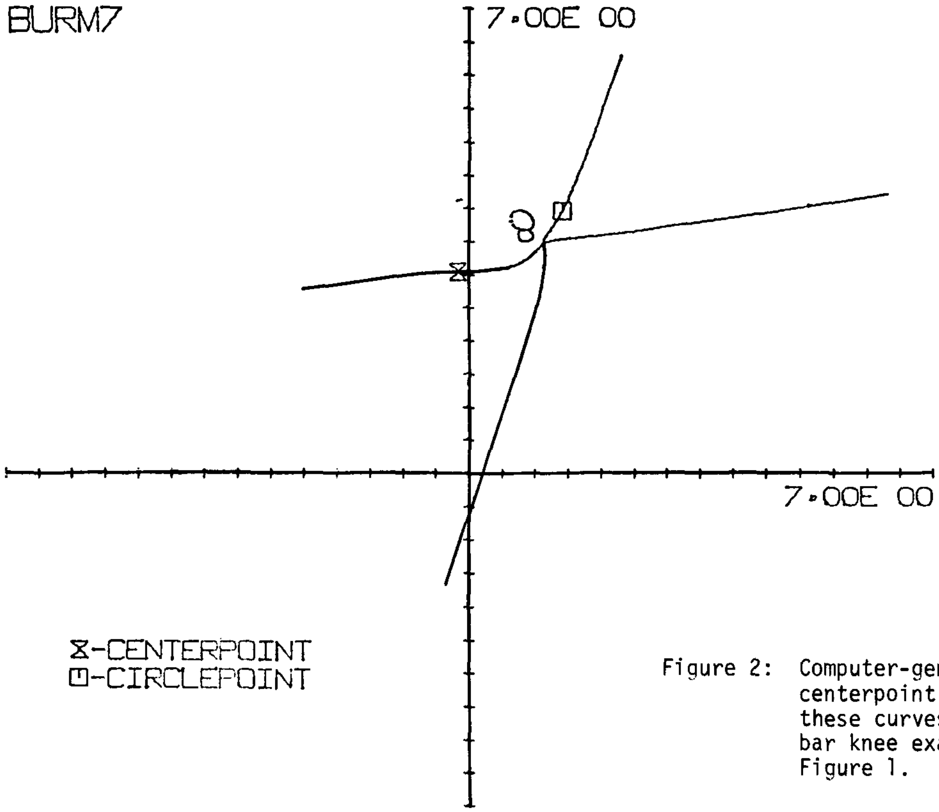

Figure 2: Computer-generated Burmester circlepoint-centerpoint curves. Pivots chosen from these curves would yield polycentric four-bar knee exactly matching motion shown in Figure 1.

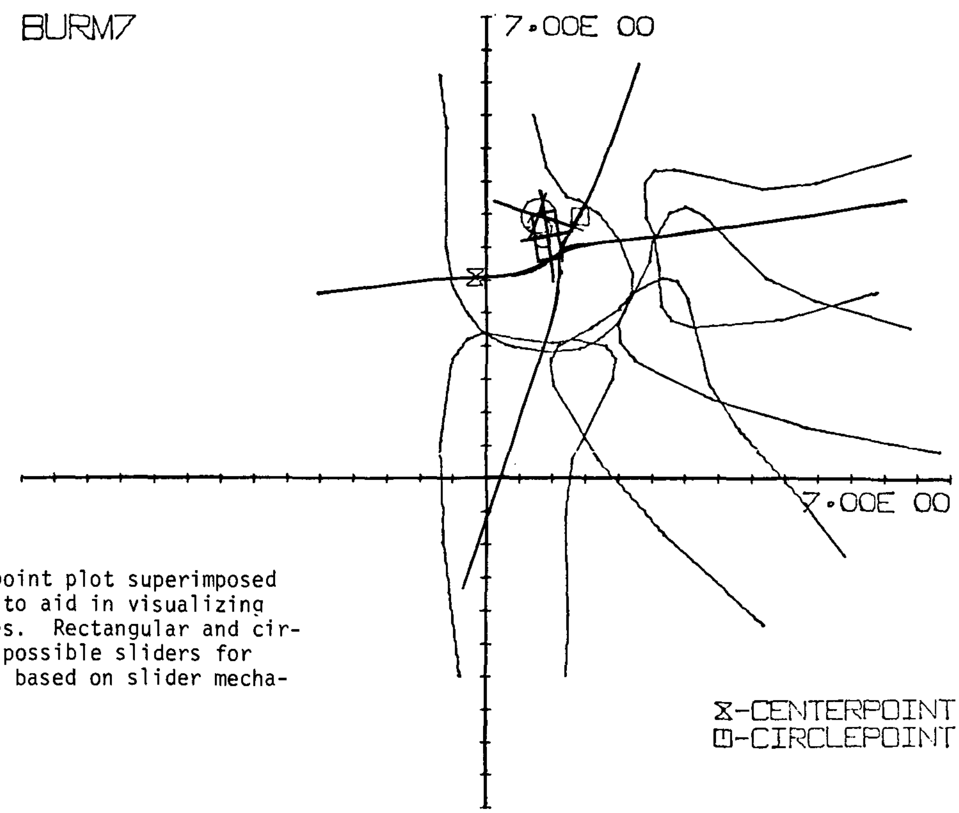

Figure 3: Circlepoint-centerpoint plot superimposed on femur and tibia to aid in visualizing design possibilities. Rectangular and circular symbols show possible sliders for physiological knees based on slider mechanisms.

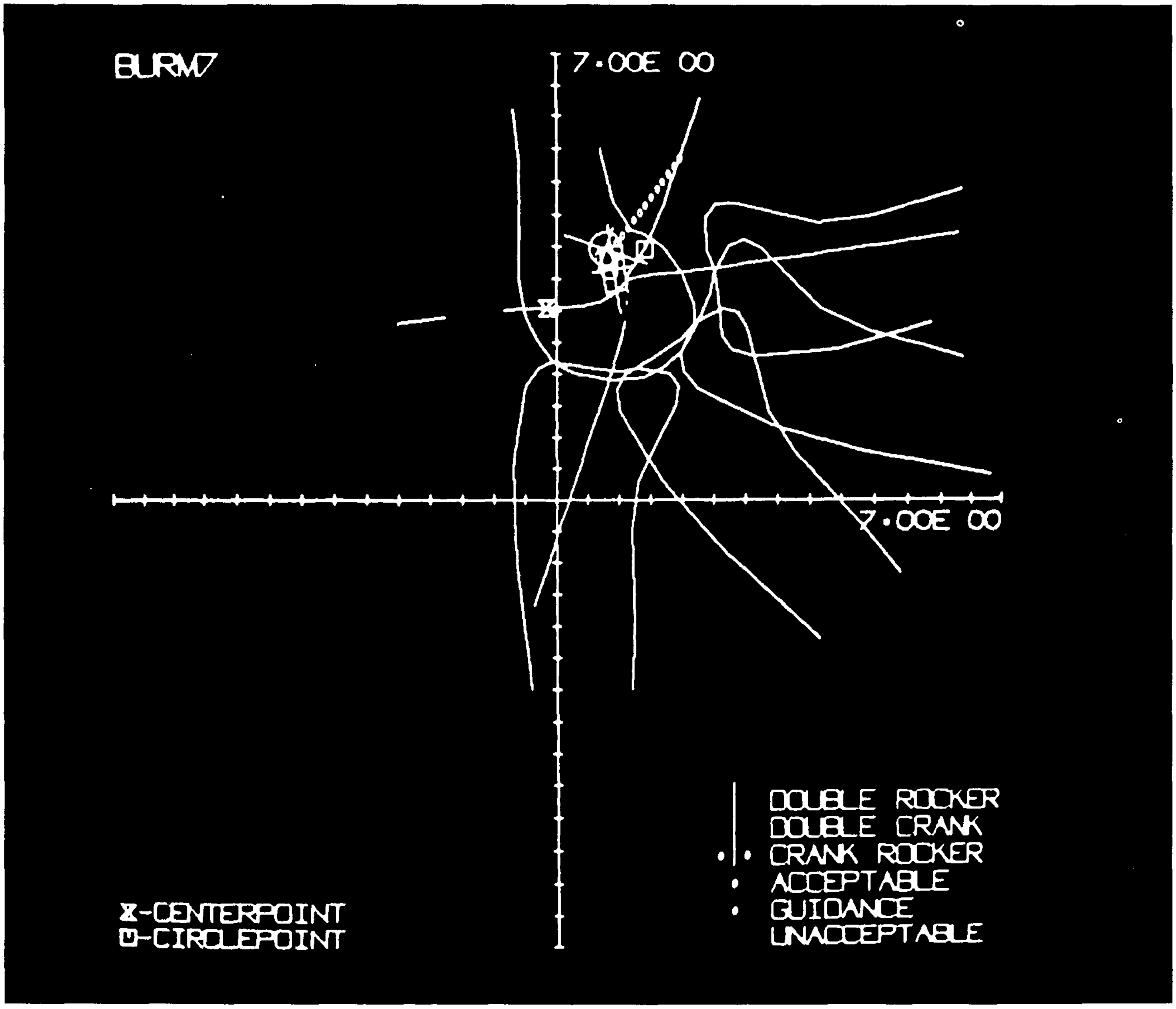

Figure 4: Typical scope display showing selection cursor bouncing between possible circlepoint and centerpoint. Flashing legend indicates mechanism based on this choice would be acceptable.

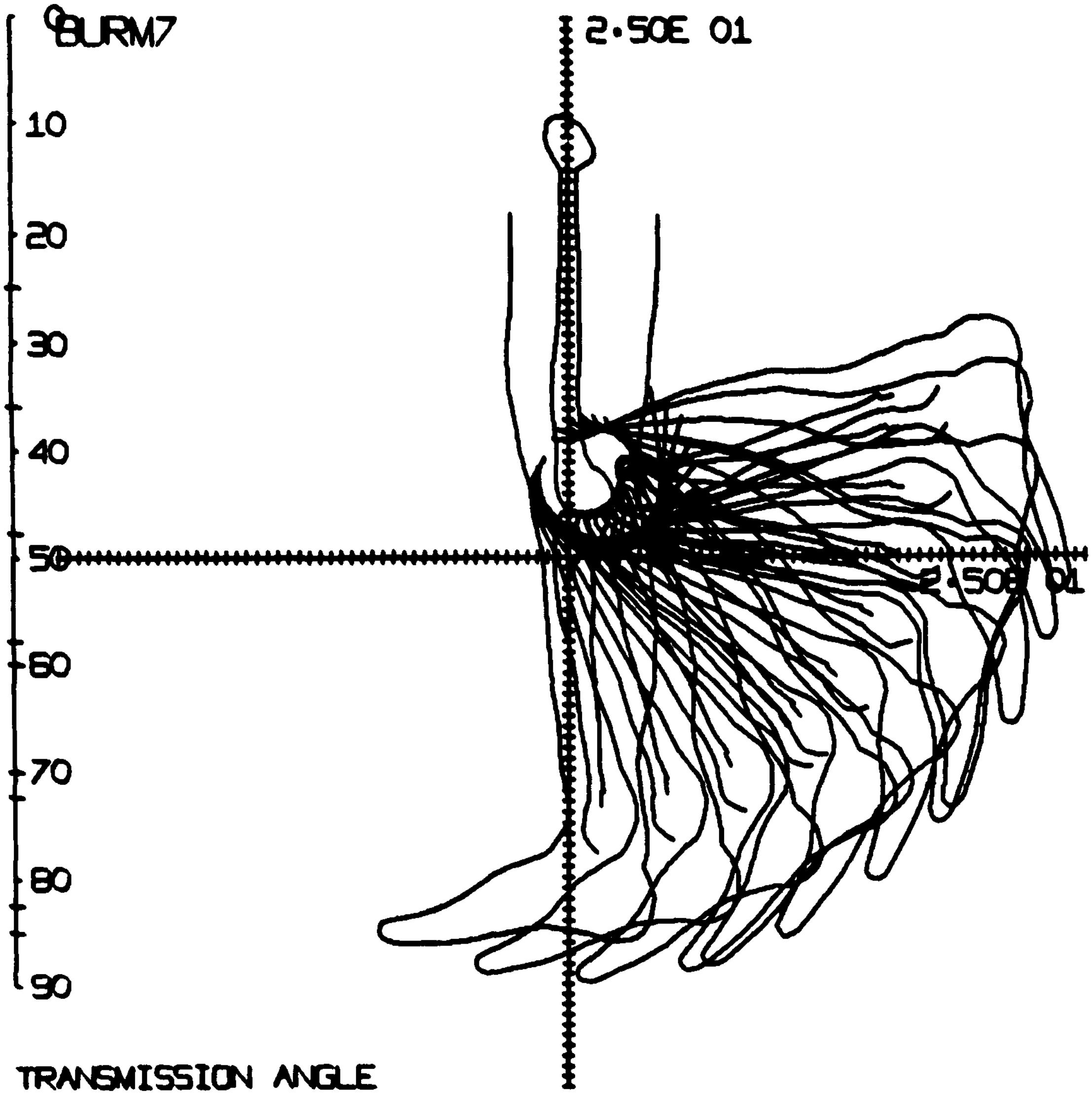

Figure 5: Tentative linkage choice being animated on display screen.

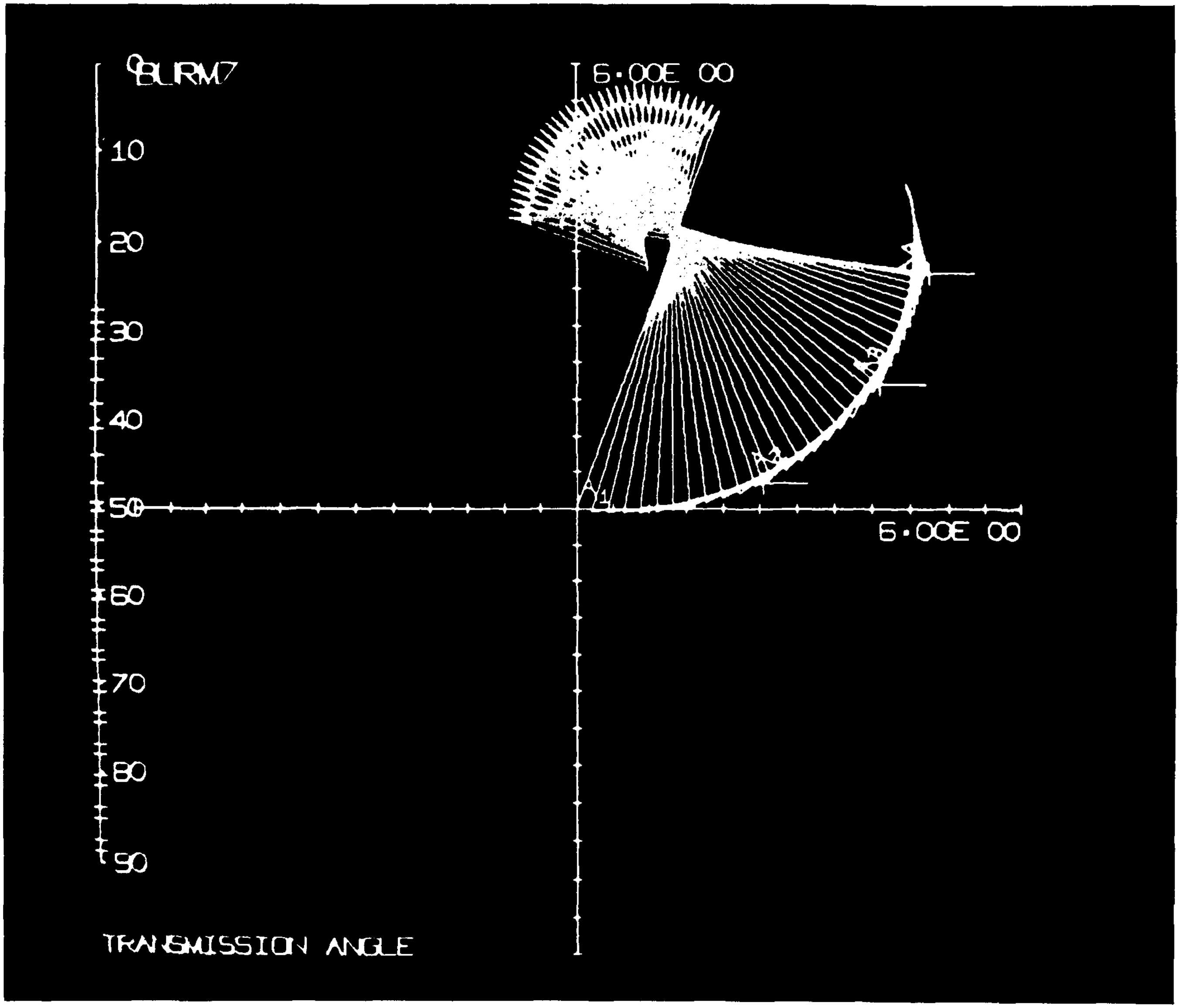

Figure 6: Slider-crank polycentric knee linkage behavior being studied over entire range of leg motion.

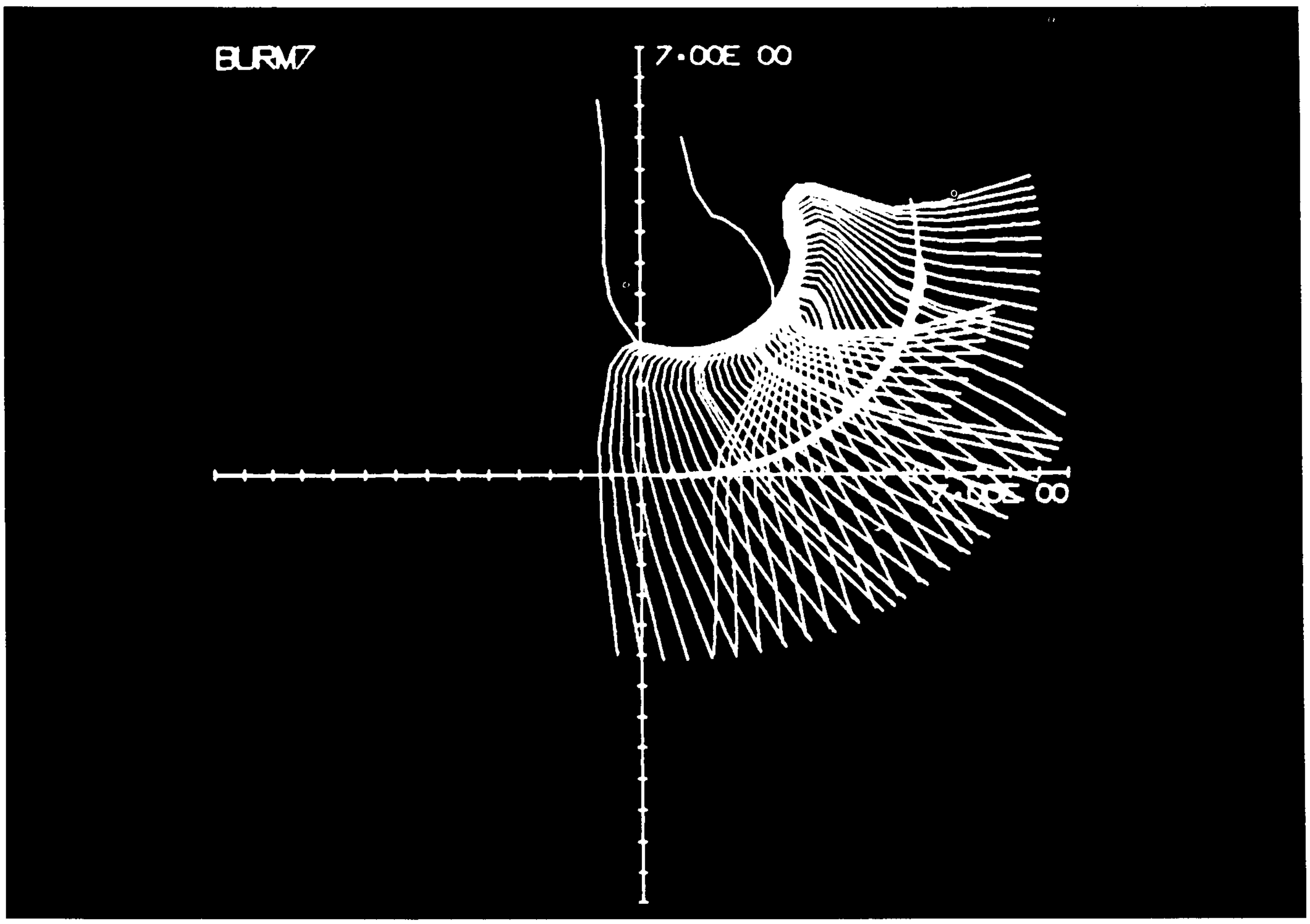

Figure 7: Blow-up of knee joint motion produced by linkage of Figures 5 and 6.

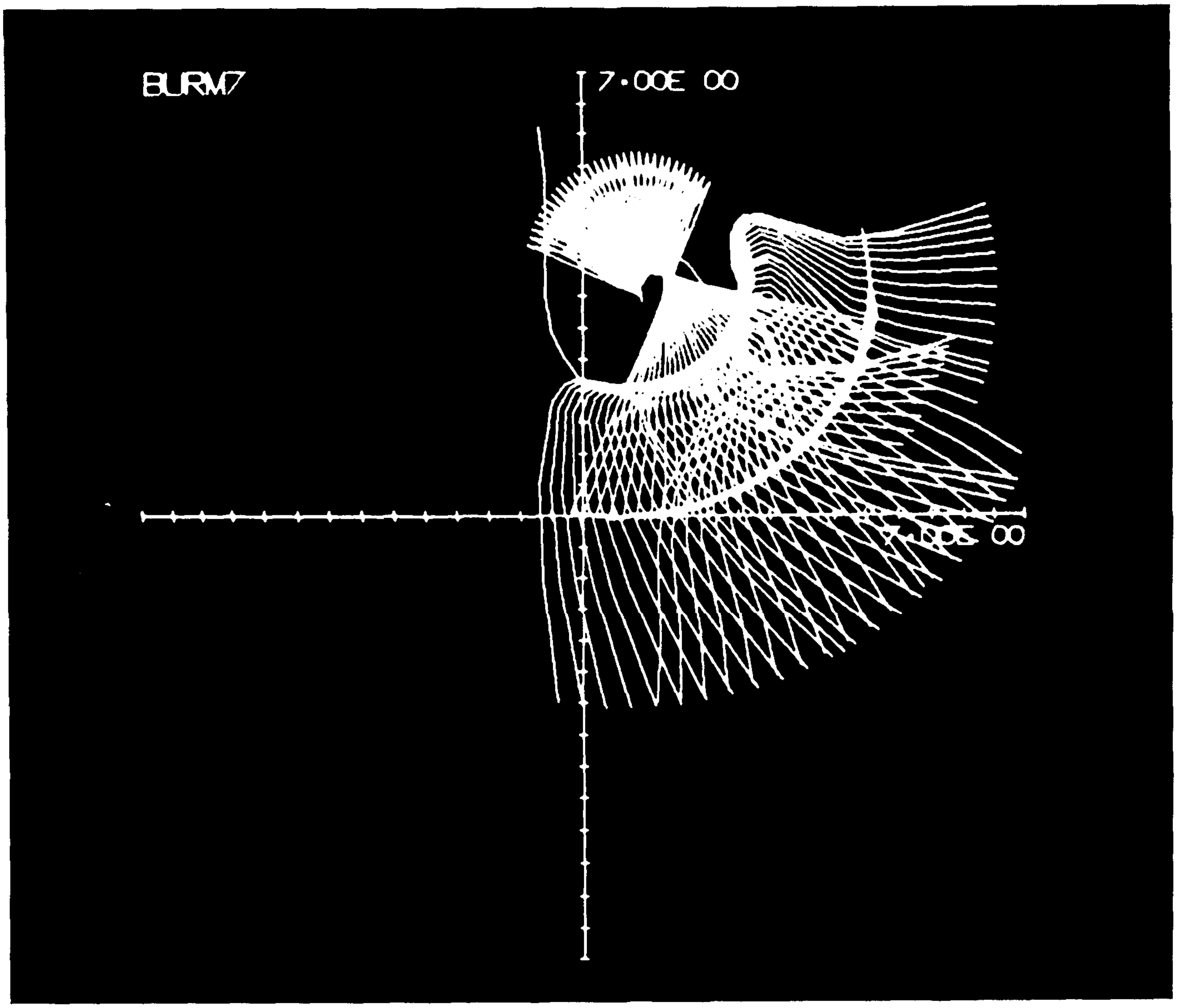

Figure 8: Superposition of linkage on joint being guided by linkage.

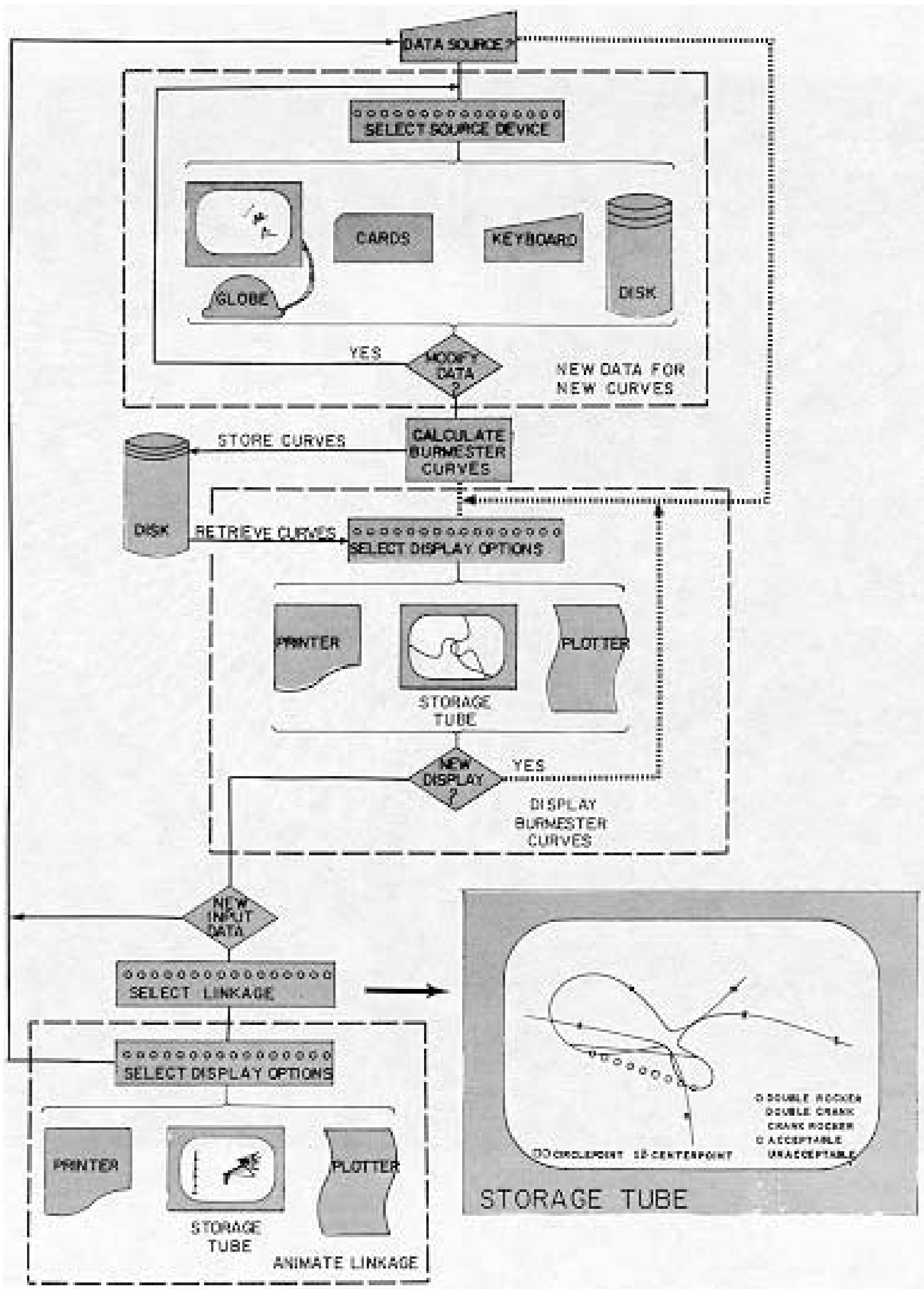

Figure 9: Program Organization.