Design approach for a Highly Accurate Patient Positioning System for NPTC

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Introduction

The support and alignment of the patient is a crucial element in the overall beam delivery system of a Proton Therapy Center. Patients must be well immobilized and precisely aligned with the treatment beam to take full advantage of the dose localization potential of this treatment modality. A patient positioning system (PPS), especially when used with a gantry beam, must permit proton beam entry from any oblique direction, without danger of collision with the gantry or beam shaping hardware.

The precision requirements of the NPTC PPS necessitated a 'clean-slate' design approach to developing the appropriate mechanism. General Atomics (a major subcontractor of IBA, the equipment vendor) developed a robotic approach based upon linear motions. In collaboration with an MIT robotics group, this design was analyzed from the perspective of accuracy including an engineering analysis of possible positioning errors and their correction through software.

Specifications and Design Constraints

The specifications of the PPS system follow from five basic clinically motivated requirements:
· Clinical Accuracy requirements
· Minimum Patient Movement
· Minimum Treatment time
· Maximum Patient Workspace
· Safety
The PPS specifications cover aspects of alignment, physical structure and safety. .Some of the specifications are summarized below.

<u>Alignment</u>
· The patient support system must be able to support at least 98% of all potential patients in such a way that all points in any conceivable target can be accurately and reproducible aligned **to the beam** to within ±0.5mm of their intended position.

<u>Adjustability</u>
· The couch and gantry together should have 6 degrees of freedom (3 translations and 3 rotation)
· It should be be compatible with remote patient positioning followed by transport to the treatment room, in order to minimize the setup time in the room.
· The patient positioner can present any point an a 50cm x 50cm x 40cm (vertical) working volume at the gantry isocenter through motions performed by linear and rotary positioners.

<u>Physical Structure</u>
· The PPS should present any point in a supine patient at gantry isocenter with the patient's orientation in the horizontal plane at any angle within a ±95° range
· The couch structure must be larger than the patient.
· Space must be allowed for ancillary equipment, such as necessary life support equipment, that must be attached to the couch.

<u>Safety</u>
· Space for the constraints that hold the patient in accurate position with respect to the couch must be provided for.
· A Buffer zone space between components must be allowed to accommodate the overtravel that occurs between the time that an interlock violation is detected and the PPS actually decelerates to a stop.

In order to complete the design of the PPS several other issues had to be considered. For example, the specifics of the mechanical configuration and the associated control algorithms are strongly coupled to the specifics of the gantry design and the beam source-to-aperture distance. These constraints require that isocentric rotation of a target on the couch must be accomplished using compound motions of the couch translation axes.

To ensure an acceptable patient setup timeline, small adjustments in the beam direction/position relative to the patient must be accomplished without large changes in patient setup positioning. Maintaining the accuracy of the original setup point in is achieved by including pitch and roll degrees of freedom with small dynamic range.

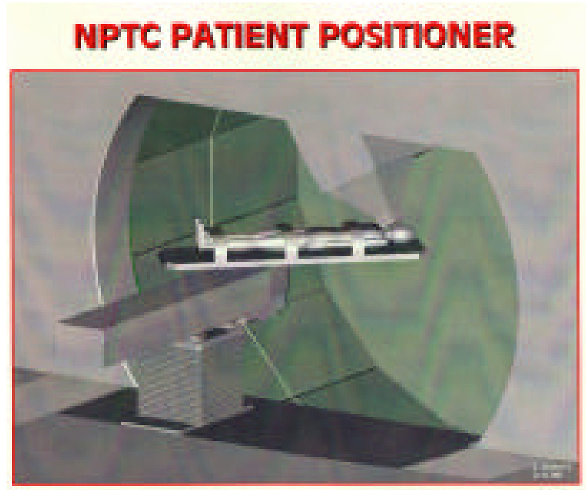

Figure 1

Modern robotics techniques allow the objectives to be achieved, but the mechanisms required are significantly larger than found in conventional positioners. The equipment consists of a patient support couch together with a number of linear and rotary positioning mechanisms, drive motors and control devices. By locating the larger mechanisms under the floor, as illustrated in Figure 1, the intrusion of the positioner in the treatment room is acceptable and the complexity largely transparent to the therapist and patient.

PPS Configuration

Figure 2 shows a side view of the PPS in the treatment room with the Gantry. The PPS travels laterally on rails under the floor. The other movement mechanisms are integrated in the PPS joints. The couch is supported on a turntable (rotary axis) allowing the couch to rotate about a vertical axis. The design accommodates supine patients up to 188 cm in height and 300lbs in weight. The resulting motion envelope that the PPS can sweep out is shown in figure 3. The key design parameters of the PPS are summarized in table 1.

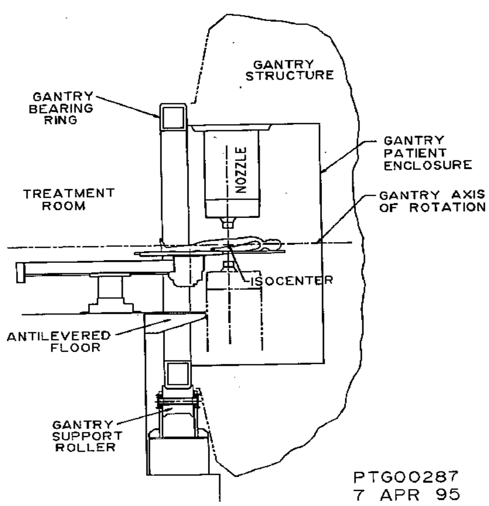

Figure 2 View of Treatment Room

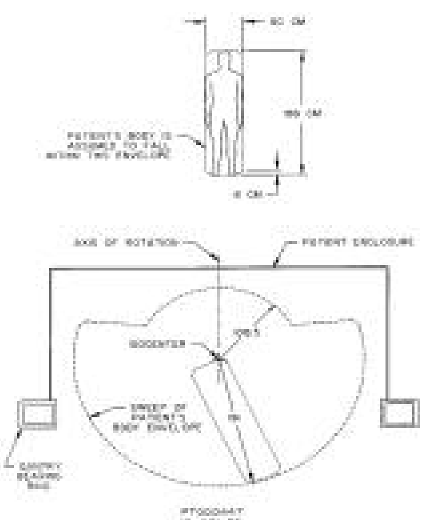

Figure 3 Working Envelope of PPS

Table 1. PPS design parameters

Parameter Description	Requirement

PPS couch operating envelope	see Figure 3
Couch treatment volume	50cm x 50cm x40cm
Lateral Axis Stroke	225.6 cm
Longitudinal axis stroke	147.3 cm
Vertical axis stroke	56 cm
Rotary axis travel	±90° for treatment ±180° for patient handling
Miniminum length of patient body space on couch	238 cm
Maximum Patient weight (Normal Operation)	300 lbs
Maximum Patient weight (Reduced Accuracy)	400 lbs
Pitch angle adjustment	± 3°
Roll angle adjustment	± 3°
Couch moment rating at rotary axis	920 ft-lbs.

The overall PPS operating envelope is a major driver of the gantry design in that it sizes the minimum inner diameter of the front gantry bearing ring. Since the patient must be rotated 90° with respect to the gantry axis of rotation, the radius of the gantry ring must be substantially larger than the height of the patient.

The patient couch assembly mounts directly to a load cell. The load cell provides a means of measuring a patient's weight and the center of gravity position of the couch during treatment. The load cell will acquire the data necessary for an algorithm to compensate for the deflection caused by the variable weight and location of the patient on the PPS.

Design Approaches for High Accuracy PPS Designs

The following table summarizes the design approaches that may be envisioned to meet demanding accuracy requirements.

Table 2. High Accuracy PPS design Approaches

Technology	Measurement Type	Design Approach	Feasibility	Mechanical Costs	Software Costs
Mechanical	'None'	**Mechanically Rigid Structure** (Small Clearances and Backlash)	Low	$$$	$
↑	Periodic Msmt. with Feed-Forward	**Good Mechanical Structure with Software Correction** · Robotic Arm · Conventional Motions	Good	$$	$$
↓	Real-Time Msmt. With Feedback	**Structure with External position Verification** · Mechanical (robotic) position measurement · Optical Laser target system with multiple lines of sight	 Good Good	 $$$ $	 $$ $$$
Software					

We have chosen a good mechanical structure with a high degree of reproducibility which uses software position corrections to obtain high accuracy.

Accuracy Calculations

The specifications call for a PPS on which a target can be accurately and reproducible aligned **to the beam** to within ±0.5mm of their intended position. This specification is a system level specification. In the non-ideal world, there will be mechanical errors which result in misplacement of the PPS and the Gantry and the Beam Delivery System elements which result in misplacement of the beam. The combined system must be capable of delivering the beam to a point in the patient with an accuracy of ±0.5mm and reproducibly to ±0.5mm.

The definition of accurate alignment here, is a specification of an absolute, rather than relative, positioning of a rigid patient. That is, based upon the settings of the PPS encoders, any PPS position can be achieved by programming in only the desired destination parameters - without any intermediate operator input or test and adjustment steps. . Reproducible alignment, by contrast, is a specification of the precision of the structure. Once a target location is determined for a given PPS setting, how close does that location reproduce once those settings are used after the PPS has been positioned elsewhere.

In a collaborative effort among MGH, General Atomics and MIT, an error analysis was performed using engineering design parameters of the PPS. Each of the mechanical components that might contribute to an error in the PPS position was considered. This included six general main sources of errors

a) Rail Curvature Errors
b) Assembly / Mounting errors (e.g. mounting angles)
c) Deflections - Elastic deformations
d) Measurements - actuator errors
e) Machining errors
f) Backlash and Clearances

Due to the cantilevered design of this system, small angular errors can be amplified to significant treatment point errors. For example, a 1 mrad angular mounting error of the base plate can contribute (through the 2.5 meter lever arm) to a 2.5 mm vertical misplacement of the treatment point.

These errors can be divided into two main types; repeatable and random errors. Repeatable errors are those whose numerical value and sign are reproducible for any given PPS configuration. For example the pitch of a screw (not considering wear) may not be exactly as specified, but will result in the same PPS position for a particular actuator setting. Random errors are errors whose value or sign changes. Examples of these include backlash and machining clearances. We also treat as random, for the analysis, that part of the repeatable source errors that are smaller than the measurement accuracy, since that part of it may be difficult to correct. Note that due to the leverage, it may be possible to measure the results of small errors at the treatment point. However it may be difficult to isolate the effect of a single such error. The issue of measurements of error is important for the PPS operation. Repeatable errors can be taken into account in PPS positioning software. It remains to determine if the random components contribute to a total error within the required ±0.5mm.

An algorithm was developed for calculating these treatment point errors as a function of the configuration setting the of PPS and the engineering source errors. Kinematic analysis of the manipulator includes defining seven reference frames, one at each moving joint. There are 6 such joints and the seventh reference frame is the treatment point, or the “end-effector”, in robotics terminology. The relative position and orientation of a reference frame $\mathbf{F_i}$ (i=1 to 6) with respect to the previous reference frame $\mathbf{F_{i-1}}$ can be expressed with a 4x4 matrix **Ai** with the form:

$$A_i = \begin{pmatrix} Ri & Ti \\ 0 & 1 \end{pmatrix}$$

Where Ri is the 3x3 orientation matrix and T is the 3x1 vector of coordinates.

At the origin of each reference frame, the engineering errors in that frame can be combined into 6 generalized errors. Thus a total of 36 generalized errors can be calculated and used to determine the ‘end-effector’ error. The position and orientation of a frame $\mathbf{F_i^r}$ after the inclusion of errors, with respect to its ideal location $\mathbf{F_i^i}$ is dependent on a 4x4 error matrix $\mathbf{E_i}$. The final location of the end effector is the product of the various **A**s and **E**s.

Figure 4 is a plot of the displacements of x, y, and z at the treatment point from the ideal (0) position, for 189 PPS configurations spanning the PPS workspace. The errors displayed here include all reasonable engineering source errors summed arithmetically.

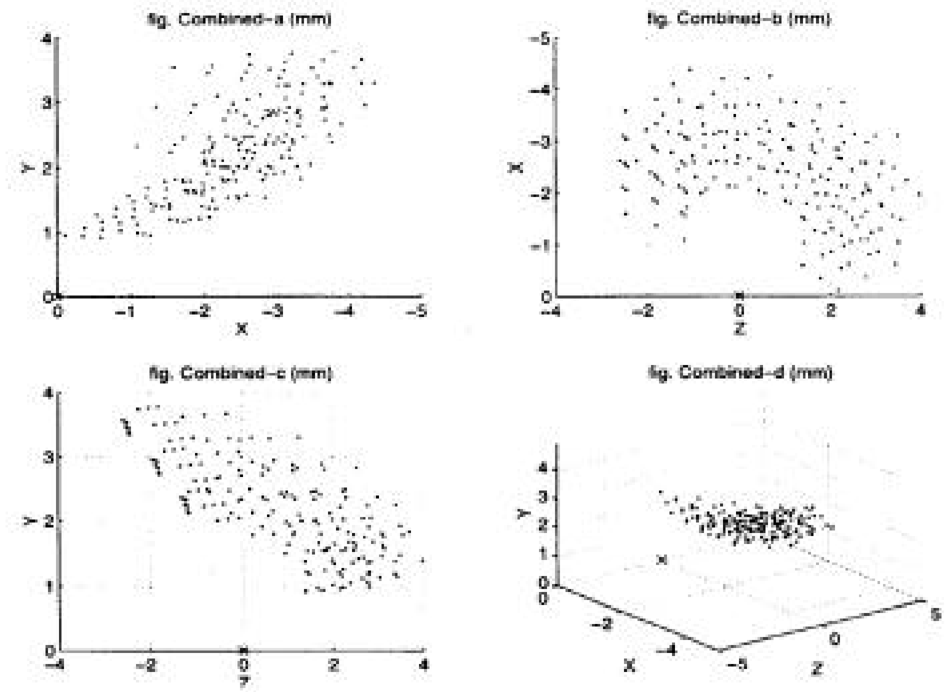

Figure 2 PPS Errors (Arithmetic Sum)

For an idea of the worst case scenario, the repeatable errors can be added with an absolute sum. The repeatable errors are added arithmetically to obtain an estimate of the PPS accuracy with no calibration. The random (unmeasureable) part of the repeatable errors are added through RMS to simulate the absolute accuracy if a correction of the repeatable errors is achieved. The truly random errors are RMS summed to obtain an estimate of the PPS repeatability. Table 3 summarizes the accuracy and repeatability prediction for the PPS. The third column of Table 3 includes the remaining uncertainty with which the beam can be misplace relative to isocenter caused by the gantry and beam delivery system while achieving the spec of beam to patient alignment of ±0.5mm.

Table 3. Calculated Performance Accuracy of PPS

Error Type	**Type of Analysis**	**Treatment Point Error**	**Gantry Error Budget**
Repeatable	Absolute Sum	10.11 mm	--
Repeatable	Arithmetic Sum PPS Absolute accuracy No calibration	5.48 mm	--
Repeatable (Correctable)	RMS PPS Absolute Accuracy Calibration	0.38 mm	0.33mm
Random only	Repeatability	0.10 mm	0.49mm

Software has been developed to calculate these errors for an arbitrary functional form of the engineering source errors. Currently work is underway to develop an optimized measurement program with the goal of characterizing the significant repeatable errors. Measurements of the configuration dependence of either the generalized errors and/or the engineering source errors will be conducted and used for a software correction algorithm.

Collision Avoidance

In order to meet the safety specifications of the PPS, a number of safety systems are being designed. Table 4 summarizes some of the related safety interlock devices.

Table 4. PPS/Gantry Safety Interlock Summary

Safety Mechanism	Purpose of Safety System
Conventional Hard-Wired Interlocks	Protect against incompatible sequencing of equipment, both for collision hazard protection and equipment safety. Protect against collision between the PPS and the patient enclosure walls.
High Speed Permissive Interlocks	Reports when the equipment is operating such that all moving axes are separated by a buffer zone that leaves room to decelerate to a stop.
Pendant Deadman Switch	Prevents motion unless the operator is holding the switch depressed. Causes a "soft" (position tracking not lost) stop when released.
Crash Stop Switches	Causes a stop as rapidly as possible (position steps may be lost). Provides an independent redundant backup to the deadman switch.
Nozzle Collision Detection	Uses load cell on PPS to detect collisions.

The high speed permissive interlocks is a General Atomics innovation which will control in what physical working area, the PPS must be moving at slow speed. In addition to the above there will be provision of identification of short and long couch extensions.