A Stereoscopic Restitution Environment for 3D Analysis of Gait

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Abstract

We propose an interactive tool integrating real-time stereoscopic display of gait motion with kinematic information of anatomical angles to improve the 3D analysis of motions coming from optical registration devices.

key words : virtual environment, 3D interaction

1 Introduction

An interactive tool integrating real-time stereoscopic display of gait motion with kinematic information of anatomical angles is proposed to improve the 3D analysis of motions coming from optical registration devices. We first recall the standard context of such analysis and we show how we can improve the decision making environment of the clinician around a simple stereoscopic restitution. Our approach covers the two following aspects : first, the 3D interaction environment is designed to enhance the viewing motion around the joints and second, the great flexibility of the environment model allows to translate various information of the standard kinematic analysis into meaningful 3D entities with synchronized real-time display of the gait motion.

2 3D analysis of gait motion

Optical registration devices know a widespread use in 3D motion analysis because they fulfill a large set of requirements for such a task : it is a non invasive, it is wireless within a sufficient configurable volume for ease of measurement, it provides real-time measurements of many markers located on the body (usually around 20), the automatic reconstruction of the 3D location of markers is now very precise (within the millimeter) and finally the location processing requires a reasonable time on a PC. All these qualities make these devices very popular for medical analysis of motion.

However, the resulting information of such device is not yet the suitable information for medical analysis of motion. Figure 1a recalls the three major processing steps related with this acquisition technique. The first step is now automatically made by the device with a good precision (less than a millimeter for a measurement volume around eight cubic meters). In fact, the uncertainty over the 3D location of the markers is less than their local shift in position due to the deformation dynamics of underlying soft tissues. From this information the second processing step is to derive the anatomical axis. Many proposition have been made to overcome the position uncertainty introduced by the soft tissues. We rely on a new technique currently developed by P. Genoud for the lower body [1]. As a result we obtain the anatomical frame associated with the pelvis, the thighs and the legs. Usually, the final data processing is to interpret the relative orientation of the distal limb with respect to the proximal limb in terms of a sequence of Euler angles. The selected Euler Angle sequence is chosen to highlight two anatomical angles. The choice of the angle order is dictated by the requirement of minimizing the errors on the resulting values and as a consequence the angle with the largest range of motion is chosen as the first one. In a gait motion it is the flexion-extension angle and its axis is fixed in the proximal anatomical frame. The third one is the rotation along the distal limb long axis and as such it is fixed in this frame. The second Euler angle value conveys less meaning for three reasons : its rotation axis is mobile with respect to both distal and proximal anatomical frames, its value inherits the discrepancies introduced by the hypothesis of a fixed axis of rotation for the first angle (especially for the knee) and the orthogonality of successive axis. As a consequence, the clinician cannot take this information into account and has to rely on other investigation tools.

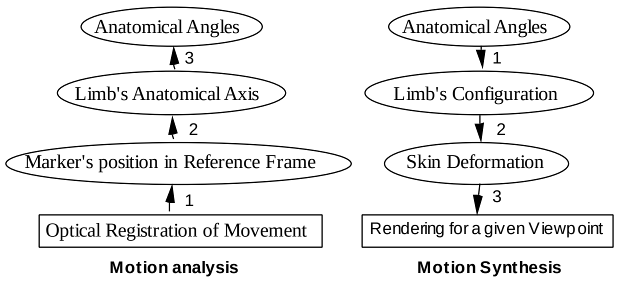


Figure 1a Analysis 1b Synthesis

Our goal is to combine the two final levels of analysis *i.e.* kinematics of the limb approximation and kinematics of the resulting Euler angle sequence. We propose to integrate the information of the Euler angle variation within the 3D environment of the virtual limbs and to synchronize this display with the real-time display of the motion. Moreover, we want to restore the initial 3D environment of the gait motion performance by choosing a stereoscopic display. In some ways, the clinician is given back the usual environment to exert his expertise. This point is important to mention in the context of Cerebral Palsy patients who have difficulties to perform repetitive gaits. Also, in such a case the motion may be difficult to process with the optical registration device. The following section establishes the configuration we have retained based on a review of other experiences in Virtual Environments and our criteria of 3D interaction.

3 Virtual Environment Techniques

We first review current experiments of Virtual Environments with two objectives : the first is to retain a configuration which adds significant enhancement to the current techniques of 3D analysis of gait ; the second is to prevent the burden and troubles encountered with some of the current 3D interaction techniques. Our goal is to provide an environment where the clinician can still evaluate the motion with traditional 2D graphics tools and also master at will the motion display with a stereoscopic restitution integrating pertinent and consistent information.

3.1 General performances

Virtual Environment techniques are better known among amateurs by a few impressive experiments where the participants feel as if they are "immersed" in another world, *i.e.* a Virtual Environment (therefore noted VE). The feeling is accentuated by the possibility of freely moving and interacting with elements of this environment via various devices. The devices and techniques allowing the creation of a VE have been now under evaluation since a few years and some conclusions can be drawn regarding our context of interest [2][3]. We will examine three major criteria (Economical, Performance, Ergonomics) from some real experiments with these techniques and establish our choice based on our specific requirements.

Economical : most of the well known VE experiments are still very expensive especially due to the high requirement put on the display capabilities and the interaction devices [2]. As such most of them still belong to research labs. Nevertheless, the computer monitor approach with liquid crystal shutter glasses and tracker is a promising configuration which provides stereoscopic vision and fulfills a large range of requirements as discussed in the next sections.

Performance : the full immersion paradigm is still years from general clinical use. Shortcomings of VE techniques are severe and impose serious limitations on applications. Most of these limitations are connected with the visual restitution of a three dimensional environment. Until now, the head mounted display technology suffers a low resolution (typically 320x240 pixels) and a low display performance (in terms of polygons/second) which prevent from displaying detailed model of the environment while preserving the minimum rate of ten images/second for a real immersion feeling. For example, in [4] the integration of a surgical simulation system into a Virtual Environment permitted to evaluate the potentialities of the full immersion system of the NASA Ames Research Center. This simulation system is presently dedicated to leg studies. According to their experiments, the redraw rate was approximately 10Hz for a bone and decreased to 2Hz for the entire leg (around 4000 polygons). Another general problem is related with the tracking devices of the participant's head or hand. The current technology introduces a lag-time (latency) which is difficult to overcome with predictive filtering due to noise [2]. On the other hand, the stereo glasses and computer monitor approach has a small field of view which prevents a sense of immersion but it provides better resolution (typically 1280x1024 on a Silicon Graphics workstation) and higher display performance[5][6].

Ergonomics : two major aspects must be considered here. First, the comfort aspects cover the physiological variables. It has been reported that the latency introduced by the tracking devices may be nauseating [2]. Also, the fact that the eyes always accommodate to a short distance in a head mounted display may strain them rapidly. Second, the man-machine interaction aspect covers the cognitive load of this new interface context. This is in fact the main challenge of Virtual Environments because the technological limits are bound to vanish. The main question is how is it possible to translate the traditional 2D desktop interface to a 3D environment ? This is a major ongoing research stream in itself [7]. The simplest approach is a direct dimensional shift of 2D items into a 3D environment. For example, 2D curves resulting from a surgical simulation setting can be visualized as 3D floating boards in the same VE as the 3D leg model [4]. The main drawback of full immersion techniques also finds its illustration regarding this criteria. In fact, as the participants are fully immersed into the VE, they cannot maintain their visual feedback loop with the real world. So, standard input devices (mouse, buttons, keyboard) becomes very difficult to use [4]. On the other hand, the SpaceBall device which is a 6 degree of freedom force/torque sensor is well suited to VE because such force and torque input can easily be mapped to increments in position and orientation of any solid in a 3D space[3]. Unlike the SpaceBall which is dedicated to desktop like environments, the DataGlove is a device commonly used in full immersion context because it is worn by the participant. Its position and orientation is tracked by the same technology as the head mounted display. In addition, this device provides a measurement of two degrees of flexion-extension for each finger[3]. Its main advantage is its continuous availability but, according to [4], the use of hand posture as input event is somewhat limited by the requirement that they be easy to enter when desired and unlikely to enter when not desired. These authors reported that five to six postures is about the limit for comfortable use. Finally, the less ambitious configuration of stereo glasses with monitor does not present such a strong delimitation of virtual and real environments and the participants can still manage a large part of the interaction with traditional means while advanced features (as flying through the VE) are easily carried on with a SpaceBalll.

Requirements : this evaluation of VE techniques has highlighted the advantages and limitations of VE technologies and the associated man-machine interaction. We should now precise our own requirements to know if VE techniques can match our

needs. Regarding our problem of 3D analysis of motion we have stated the following criteria, from high to low priority :
- synchronized display with the time base of the analyzed motion, only a constant scaling factor can be admitted to slow down (or up) the displayed motion.
- stereo restitution with freedom of viewing
- Enhanced Man-Machine interaction.
- Rendering of relevant information.

Finally, according to our requirements and the previous criteria, the stereo glasses with monitor for output and the SpaceBall with other standard devices for input is the best candidate configuration for our needs. It is interesting to note that such configuration has been retained to identify potential collision problems with a virtual prototype of the Hubble telescope for the simulation of the deployment of the new correcting optical bench [5]. Following the same approach, we also consider that full immersion is not vital for 3D analysis of motion because our goal is to provide a better understanding of a local phenomenon rather than to convey a global feeling about some continuous environment. Moreover, the interactive specification of the viewing motion is perfectly handled with a SpaceBall device which allows the clinician to examine carefully its patient's motion without physically moving around. Useful considerations regarding the projection settings of stereo glasses can be found in [8].

4 Enhancing the 3D analysis of gait

We briefly recalls the original objective of our animation system prior to show how it can be adapted to 3D analysis of motion. We especially stress the integration of traditional 2D information into the VE.

4.1 Overview of the TRACK system

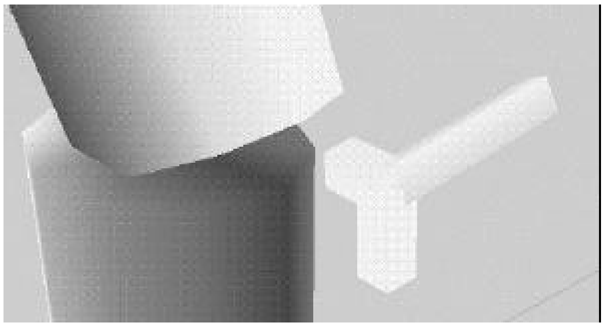
The general structure of an animation system as TRACK basically responds to the data flow of Figure 1b. In such systems the human model is simplified to reduce the dimension of the control space. Motion designers have access to angles similar in nature to anatomical angles and they can specify their behavior over time with various techniques [9]. As the human model is organized in a hierarchical fashion [10], the motion of the angles close to the hierarchy root drive the motion of the lower level limbs and so on. Finally, the skin deformation is computed from the resulting posture and a set of volumes crudely approximating the muscles shapes [11]. By now, these models are still very far from the clinical reality but, as our models of human anatomy will improve, we foresee an interesting synergy of the synthesis process with 3D analysis where the simulation of the realistic skin deformation will help to improve the reconstruction of anatomical frames from the markers locations.

Thanks to the general purpose representation of our 3D hierarchy, we are also able to represent marker sets as well as the resulting solids in a very flexible way [10]. The hierarchy basic component, called the `node_3D`, is chosen to retain the geometric, topological and display information sufficient to set a frame in a 3D space An additional functionality can be associated to a `node_3D` through the binding of one typed structure. Currently used types are the following : a `FREE` type maintains a homogeneous matrix (*e.g.* for the anatomical frame situation), a `JOINT` type maintains one degree of freedom either translation or rotational (*e.g.* for the integration of Euler angles or other information in the 3D context), and a `SOLID` type holds mass and inertia matrix of a volume primitive (*e.g.* to display approximate shape of the limbs). In addition, a corresponding representation of motion based on interpolated key values for each degree of freedom has been defined [9]. The recorded motions can be associated to a hierarchy and played back with the suitable synchronization. This environment also provides a set of tools for 2D analysis of motion.

4.2 3D Interaction Tools

A 3D model reconstructed from the markers analysis is already interesting in itself if one can view it from any vantage point and especially when it can be attached to any frame in the hierarchy. For example, one can view very easily the knee motion by specifying the camera situation relatively to the thigh node_3D and moving around interactively according to the SpaceBall input.

Additional insight can be gained by adding relevant information within the 3D environment. This is the case with the Euler angle sequence deduced from the relative orientation of two limbs. This information is evaluated for each time step and displayed as three rotational vectors, with a norm proportional to their value and the suitable orientation. Moreover the derivative of the Euler angles is integrated in the display with color coding : an increasing angle is displayed in red, a constant one in green and a decreasing one in blue. The color changes smoothly according to the derivative value. Figure 2 shows the corresponding display centered on the knee joint with the set of Euler vectors slightly in front the knee. In fact, the vectors are represented by three `SOLID` and two `JOINT` rooted on a `FREE` node_3D itself attached to the proximal limb (*i.e.* the thigh). This sub-hierarchy may be positioned freely to suit the clinician viewing conditions. Figure 3 shows the corresponding hierarchy of the Euler angle display mode.



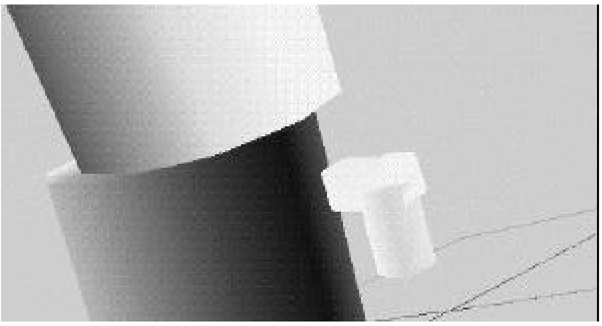


Figure 2 : a 3D model integrating Euler angle data for two different postures of the knee joint while walking.

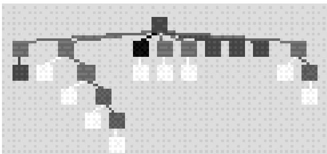


Figure 3 : The 3D environment hierarchy

Another significant step in the improvement of 3D gait analysis is to integrate an estimation of the walking phase in the 3D environment. We can evaluate it in advance for a given walking motion from the analysis of the knee flexion-extension anatomical angle. This angle is very specific and usually presents a clear indication of the beginning of a walking cycle (at heel strike). The resulting curve is analyzed according to its general double bell shape and the cycle beginning events t_i (i=1,n) are converted into `JOINT` key values as:

$$\text{alpha}(t_i) = - 2\text{pi} \quad (1)$$

The display structure associated with this phase information is composed of a `FREE node_3D` holding a `SOLID` shaped as a clock and the `JOINT` associated with the phase with its rotation axis perpendicular to the clock plane. A last `SOLID` attached to the phase `JOINT` and lying in the clock plane realizes the needle (Fig. 4). When the motion is played back, the phase is displayed clockwise and realizes a full clock turn for each cycle.

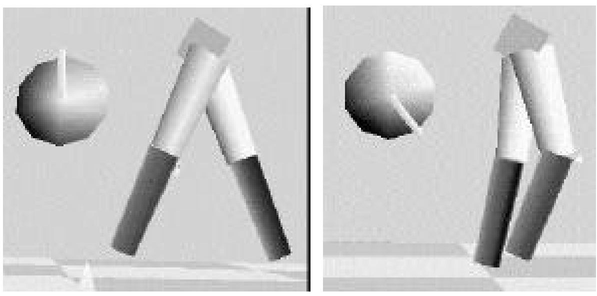


Figure 4: integrating the phase variable in 3D

5 Conclusion and future work

Our approach proves to be a good compromise of the new devices and techniques introduced in the virtual reality field for the improvement of 3D analysis of motion. Associated with the stereoscopic display of the reconstructed environment, the 3D translation of Euler angles and the phase estimation proved to be useful hints for the clinician in his analysis of gait motions. Future works will develop this trend and integrate more research results from 3D interaction field.

6 Implementation

The different software modules are developed in C language over the GL library on Silicon Graphics workstations. We use an Object Oriented interface toolkit developed at the Computer Graphics Lab of the Swiss Federal Institute of Technology (Lausanne).

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