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Reality and illusion in Virtual Studios: Axiomatic Design applied to television recording

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Abstract

This work presents the design project of a camera support structure for a Virtual Studio (VS). A brief description of VS is presented regarding both the equipment needed and the issues related to the correct matching of real foreground with virtual background. Given this scenario, an important role is covered by the camera supporting structure that allows a more correct execution of the standard filmmaking shots such as: medium shot, close-up, low/high angle shot and tracking shot. The work shows how the structure design has been carried through the Axiomatic Design focusing on how a coupled and a redundant design have been identified and solved. The approach has led to a significantly different design from classic camera support structures such as Cranes and Jibs and advanced Motion Control Rigs used in cinematography. The complexity reduction compared to Motion Control Rigs makes the designed structure suitable for a low budget VS set up.

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Keywords: Axiomatic Design; Coupled Design; Redundant Design; Virtual Studio; camera shots

1. Introduction

Nowadays television broadcasting companies have to deal with the increasing demand of enhancement of information, regarding both quality aspect and the fruition of contents. One of the emerging technologies able to satisfy this demand is the use of Virtual Reality (VR) and the set-up of the so called Virtual Studio (VS).

The Virtual Set technology [1] is used by television broadcastings of different sizes. It has evolved from high investment equipment into a low-cost tool, thanks to the amazing and sudden increase of computing ability and due to the easy and inexpensive availability of software for images and rendering. The opportunity of the real-time combination of the actors presence within a set generated by computer, has in fact important outcomes both on economic and creative perspectives. The demand of the audience for more realism in the development of a virtual set, which often represents an unreal setting or an impressive interaction between the actors and the setting, inevitably affects the technical aspects of the Virtual Studio fulfillment. The main challenge in the development of a Virtual Studio is to generate the illusion of having the actors inside a setting perceived by viewer as real and credible. In the VS, the actor plays inside a set composed by blue or green panels (chroma key) built as “U” or “L”, and the act is filmed using a camera. The images are mixed in real time with 2D or 3D background previously developed using modeling software tools. To do this, a closer connection between the real world and the virtual one is needed through the proper fitting of the lights and movements of the camera. Therefore the “real” television camera recording the actor and the “virtual” background created have to be entirely synchronized [2]. This aspect can be a challenge if we also consider that a correct prospective between the real foreground and virtual background have to be achieved [3]. Given this scenario, an accurate positioning of the camera needs to be achieved and maintained to avoid prospective issues and unnatural shadows in unexpected places. For these reasons several camera supporting structures are available on the market mainly derived from those currently used in cinematography. Jibs and dollies are the most common rig and allow only some filmmaking shots. On the other hand, Motion Control Rigs permit complex movements but they are usually very expensive. To fulfill the flexibility required by VS, a combination of all the above typology of structure is

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necessary. It generally means a huge investment often not affordable by medium and small size VS. For this reason, a new design of camera supporting structures will be here presented. The aim of the authors is to achieve a final design less complex compared with the Motion Control Rigs and suitable for a low budget VS set up. Since the design has been started from scratch, the article will present all the design steps carried through the Axiomatic Design, showing how a coupled and a redundant design have been identified and solved.

2. Design of camera supporting structure

The camera supporting structure that will be presented has been designed following the Axiomatic Design (AD) methodology developed by N. P. Suh [4]. The guidelines for defining a design standard [5] follow a scientific and systematic approach based on logical and rational processes and tools. The aim of AD is to let designers be more creative, able to reduce random search process to minimize the iterative trial-and-error process.

In AD the design activity can be schematized by using four domains: the customer domain, the functional domain, the physical domain and the process domain [6].

The customer domain describes the Customer Attributes (CAs), the functional domain (deducted from CAs) the design objectives and Functional Requirements (FRs), the physical domain provides Design Parameters (DPs) for the implementation of the FRs that will be processed by the Process Variables (PVs) defined in the process domain.

Mapping between design domains is performed following two axioms, representing the core of the methodology.

The first axiom is called the Independence Axiom and it states that the independence of FRs must always be maintained. The second axiom is called the Information Axiom and it states that among those designs that satisfy the Independence Axiom, the design that has the smallest Information Content is the best [6].

From a mathematical point of view FRs and DPs can be represented as vectors {FR} and {DP}.

The Design Matrix (A) shown in figure 1 describes the relation between the two vectors (1):

$$\{FR\} = [A]\{DP\} \tag{1}$$

In order to satisfy the Independence Axiom, the Design Matrix [A] has to be diagonal or triangular [7]. When [A] is diagonal, each FRs can be satisfied independently from its related DP. This kind of design is called *uncoupled design*. If [A] is triangular the independence of the FRs can be guaranteed when the DPs are in the correct sequence indicated by the matrix. This kind of design is called *decoupled design*. Any other form that the matrix [A] can take is called completed matrix and it represents a *coupled design*.

In this case, the design is considered unacceptable since it is hard to control that a single FR through its corresponding DP is not affecting other FRs.

$$\underset{\textbf{Uncoupled}}{\begin{pmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{pmatrix}} \qquad \underset{\textbf{Decoupled}}{\begin{pmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{pmatrix}} \qquad \underset{\textbf{Coupled}}{\begin{pmatrix} X & X & X \\ X & X & X \\ X & X & X \end{pmatrix}}$$

Fig. 1. Example of design types

Following the AD method, the supporting structure for the camera has been designed through subsequent hierarchical decompositions of FR and DP vectors. This approach consists in a *zigzagging* between functional domain and physical domain. By applying these principles, the design has begun with the definition of the FR at the highest level of its hierarchy in the functional domain. For this design concept, the following has been selected as the highest FR:

FR_0 = Move a camera in a Virtual Studio

The following DP has been selected to satisfy the FR provided above:

DP_0= Supporting Camera Structure (SCS)

If the DP proposed in the preview section cannot be implemented without further clarification, AD methodology allows to “return” to the functional domain for decomposing the FR into a lower FRs set. In this specific application FR_0 has been decomposed as follow (first level decomposition):

FR_1 = Move the camera vertically
FR_2 = Rotate the camera left/right about a central axis
FR_3 = Follow the subject within the frame
FR_4 = Move the camera parallel to the action
FR_5 = Rotate the camera up/down about an horizontal axis

The movie camera is placed in a television studio and it has to capture middle range frames. The figures are either still or moving in the frame, they are rather near and they might not fill the entire frame length-wise. As a consequence there is still an edge between the heads of the figures and the upper boundary and/or between their feet and lower boundary.

Description of the FRs:

FR_1: The movie camera has to frame from top to bottom with a vertical translation with respect to the subject (pedestal shot).

FR_2: The movie camera has to frame from right to left with a rotation about a vertical axis (panning shot).

FR_3: The movie camera has to frame getting near the subject or has to remain at a constant distance (backwards/forwards tracking shot).

FR_4: The camera has to frame moving laterally. Usually this movement follows a pre-defined path through a track place on the floor (lateral tracking shot).

FR_5: The camera has to be placed in order to shot the framed subject from the top or the bottom with a rotation about a horizontal axis (high-angle-shot and low-angle-shot).

To complete the mapping process, designer must think about all the different ways to fulfill each FRs by choosing possible DPs. It can be used analogy from other examples, extrapolation and interpolation and reverse engineering, database of all kinds [6]. Following these steps, and analyzing the camera movements defined by FR_1, FR_2, FR_3 and FR_4 it is possible to deduct that camera positions will always be identified respect to horizontal planes parallel to each other. For this reason a first attempt to define DPs has been made in analogy of the planar kinematic used by SCARA (Selective Compliance Assembly Robot Arm) robots.

Their different configurations allow the location of the end-effector at the end of the kinematic chain, only in a horizontal plane. If a camera would be mounted instead of the end-effector, that kinematic will allow all kinds of needed shots.

The following DPs showed in figure 2 are in response to the FRs listed above:

DP_1 = Telescopic pedestal
DP_2 = SCARA kinematic
DP_4 = Rail-Dolly system
DP_5 = Remote head

Description of the DPs:

DP_1: In order to allow the pedestal shot, a telescopic column lifts the SCARA system up to its positioning at different heights.

DP_2: It is a mechanism composed of three bodies: two links and one tool. They are connected each other by revolute joints whose rotational axis are perpendicular to the links, resulting in a planar kinematic.

DP_4: It is a system made of a rail fixed to the ground and a supporting structure.

DP_5: It is a module to allow pan and tilt motion required to execute high-angle/low-angle shot.

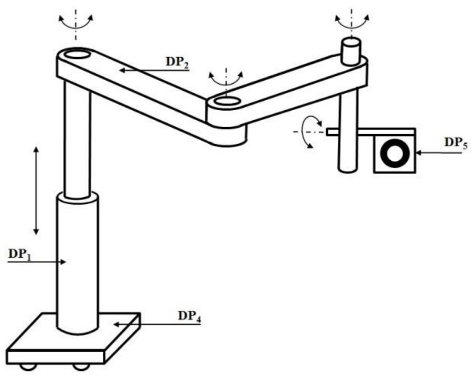

Fig. 2. First level decomposition DPs

The corresponding Design Matrix (Tab.1) provides the relationships between the FR and DP elements.

Table 1. First Level Design Matrix (coupled design)

	DP_1	DP_2	DP_4	DP_5
FR_1	X	0	0	0
FR_2	0	X	0	0
FR_3	0	X	0	0
FR_4	0	X	X	0
FR_5	X	X	0	X

As showed in the matrix, the first attempt design with this particular configuration is a *coupled design.* The first theorem of the Axiomatic Design establishes that if DPs are less than FRs the resulting design will be incomplete or, indeed a *coupled design*.

In such design based on SCARA analogy, five FRs and only four DPs were defined. So the DP_2 is the design solution parameter of both FR_2 and FR_3. The SCARA kinematic allows making frames through both panning shot and backwards/forwards tracking shot. Also the FR_4, (lateral tracking shot) depends partially from the DP_2. A design like that need to be changed in order to became an *uncoupled design* or a *decoupled design*.

On the basis of the previous observations, the issue of the project is due to the formulation of the DP_2 so the 3 DOF (Degree Of Freedom) SCARA kinematic (figure 3) has been analyzed.

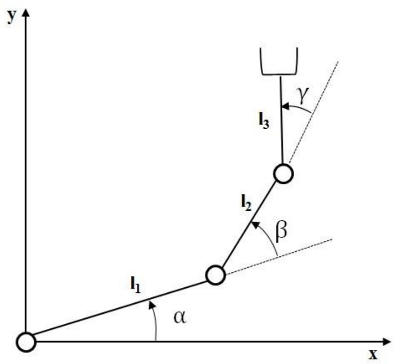

Fig. 3. 3 DOF planar kinematic

In particular, the configurations available for each combination of the three angles α, β and γ of the revolute joints that define the work space (figure 4), has been investigated.

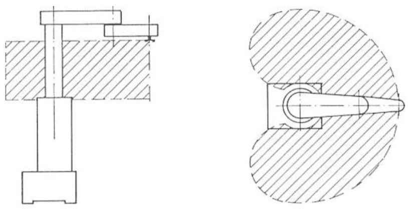

Fig. 4. SCARA work space

Regarding the application intended for this camera supporting structure, it is clear that the work space needed for the different kind of frames represents a portion of the space showed in figure 4.

The position of the camera, in fact, has to be reached following only two different trajectories: a circular path for the panning shot and a straight path for the backwards/forwards tracking shot. Therefore this two camera movements define the resulting work space as an annulus. Moreover, the mentioned frames have to be made independently, so they require an exact planning of the movement to carry the supporting element for the remote head in the desired position.

For these reasons, the DP_3 has been added and the DP_2 has been re-defined for the first-level matrix. In this manner the backwards/forwards tracking shot and the panning shot are made independent thanks to rotational DOF added by DP_3 shown in figure 5.

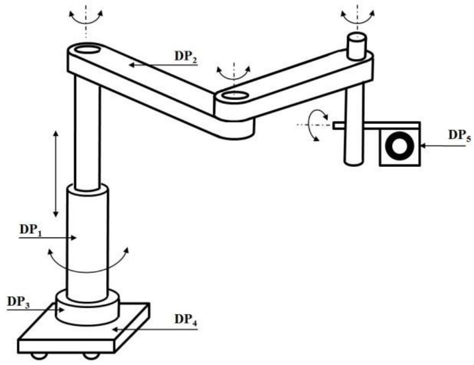

Fig. 5. New first level decomposition DPs

DP_2 = Constrained SCARA kinematic

DP_3 = Connection module between telescopic pedestal and Rail-Dolly system

Description of the DPs:

DP_2: New SCARA kinematic differs from previous because it is limited to perform only a straight trajectory to position the remote head.

DP_3: It is a module that allows the telescopic pedestal to rotate about its vertical axis.

Table 2. New First Level Design Matrix

	DP1	DP2	DP3	DP4	DP5
FR1	X	0	0	0	0
FR2	0	X	0	0	0
FR3	0	0^1	X	0	0
FR4	0	0	0	X	0
FR5	X	X	0	0	X

Elements of the Design Matrix:

A_{51}: The high-angle-shot and low-angle-shot frames depend on the maximum height reached by the camera, therefore from the telescopic column.

A_{52}: The high-angle-shot and low-angle-shot frames depend on the maximum range of the straight trajectory allowed for the camera and therefore depend on constrained SCARA kinematic.

A_{32}: The correct execution of the panning shot is independent from SCARA kinematic as long as the angles α, β and γ remain constant (superscript 1 represents that constraint).

The second level of decomposition presented below deals only with FR_2, because the chosen DP_2 is not detailed enough to guarantee a correct implementation. The remaining DPs are excluded because they are solution available on the market.

FR_{21} = Place camera at maximum radial distance.
FR_{22} = Place camera at minimum radial distance.
FR_{23} = Execute only a straight path for remote head.

DP_{21} = Sum of lengths of links
DP_{22} = Max value of β angle
DP_{23} = α angle
DP_{24} = β angle
DP_{25} = γ angle

Description of the FRs:

FR_{21}: This camera position occurs when all three revolute joint of SCARA kinematic are aligned. Camera is at maximum radial distance D respect to the telescopic pedestal to allow the limit position of the forward tracking shot as shown in figure 6.

FR_{22}: The camera is at the minimum radial distance d respect to the telescopic pedestal to allow the limit position of the back word tracking shot.

FR_{23}: It is the requested independence between forward/backward tracking shot and panning shot.

Description of the DPs:

DP_{21}: The lengths of the links l_1 and l_2 are chosen in order to permit the camera positioning at distance D so the lengths ratio r has to be defined.

DP_{22}: It is the maximum value allowed for angle β in order to permit the camera positioning at distance d.

DP_{24}, DP_{25}, DP_{26}: They are the values for α, β, and γ angles that permit the straight path motion of the camera also maintaining its orientation constant.

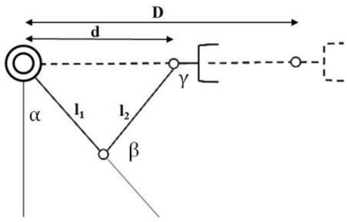

Fig. 6. Limit position of the camera for forward/backward tracking shot

Elements of the Design Matrix:

A_{21}: The variation of r affects DP_{22} because only with its previous definition it is possible to identify univocally the maximum value of β angle.

A_{31}, A_{32}: DP_{21} and DP_{22}which define the limit positions of SCARA kinematic, are necessary to evaluate the three values of the angles to be applied to the joints in order to allow straight trajectory for the camera.

Table 3. Second level Design Matrix (redundant design)

	DP_{21}	DP_{22}	DP_{23}	DP_{24}	DP_{25}
FR_{21}	X	0	0	0	0
FR_{22}	X	X	0	0	0
FR_{23}	X	X	X	X	X

The Theorem 3 of the Axiomatic Design defines a design in which the DPs are more than the FRs as a redundant design.

In particular, the FR_{23} is a function of all five DPs (4):

$$FR_{23} = f(DP_{21}, DP_{22}, DP_{23}, DP_{24}, DP_{25}) \quad (4)$$

In order to avoid such design the solution proposed is to perform the straight trajectory of the camera (backwards/forwards tracking shot) only with the variation of the angle α (DP_{23}). The value of this angle will range between a minimum depending on DP_{21} and $DP_{22,}$ and a maximum equal to π/2. A mechanic transmission will provide β and γ angles to be dependently connected with the values assumed by α during the motion.

The angles β and γ can be evaluated respect to α using the equations of the inverse kinematics [8].

As shown in the figure 7 in order to have the straight motion of the camera depending only on α, a cross-belt drive has been used. In fact, to obtain the desired motion the three kinematic elements have to rotate in opposite direction respect to each other.

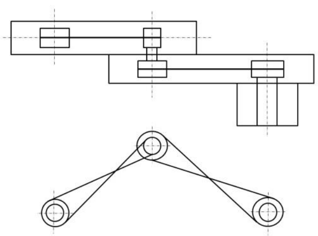

Fig. 7 Cross-belt drive scheme

In this way, the FR_{23} is dependent only on three DPs (5)

$$FR_{23} = f(DP_{21}, DP_{22}, DP_{23}) \quad (5)$$

So the design matrix takes a triangular form representing a *decoupled design.*

Table 4. New second level Design Matrix

	DP21	DP22	DP23
FR21	X	0	0
FR22	X	X	0
FR23	X	X	X

To verify the coherence of the design choices adopted, the correlation matrix for the first and second level decomposition has been built.

Table 5. Correlation Matrix

	DP1	DP21	DP22	DP23	DP3	DP4	DP5
FR1	X	0	0	0	0	0	0
FR21	0	X	0	0	0	0^2	0
FR22	0	X	X	0	0	0^2	0
FR23	0	X	X	X	0	0	0
FR3	0	0	0	0^1	X	0	0
FR4	0	0	0	0	0	X	0
FR5	X	X	X	0	0	0	X

To address the Design Matrix ideal conditions, the following Constraints must be satisfied:

1: In order to perform panning shot, the angle α has to remain constant.

2: The Rail-Dolly system has to remain in position during a tracking shot.

3. Conclusions

The design of a camera support structure was addressed using the Axiomatic Design methodology through a rigorous approach that has allowed identifying and solving critical design issues. Other issues concerning the development of a Virtual Studio were presented, paying attention to the importance of a correct camera positioning. Through the subsequent analytical breakdown of each functional aspect, characteristic of the Axiomatic Design methodology, it was possible to detail every constructive element towards minimizing the Information Content. The analysis of each Design Matrix in fact, allowed first to detect possible dependencies between the DPs and later, through a transaction *reordering*, to suggest what was the order of resolution of each FR to achieve a more efficient product design. In the application discussed, this design approach allowed not only to proceed from general to detailed aspects of the solution, but also to constantly checking the design consistency through the analysis of the Design Matrix respect of the above axioms. In this way, during the design process, choices were verified in a scientific manner, while they are otherwise analyzed at a later stage, typical of heuristics and empirical methodologies. The project was therefore developed, through the definition of the respective FRs, in relation to the specific application to which they were addressed. In particular, in the paper is shown how a coupled design and a redundant design have been discovered and resolved during the different steps of the design.

A new concept of a camera support structure significantly different from the classic ones used in cinematography has been developed. Even if it can be considered hybrid between the static supporting structure such as Crane and Jibs and the more complex Motion Control Rigs, allows standard filmmaking shots making it suitable for low budget Virtual Studio. Considering the reliability perspective further interesting AD application could be found in literature such as in [9-10-11].

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