Exploring Quantitative Methods to Study Design Behavior in Collaborative Virtual Workspaces

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***Abstract*—This paper presents a case of exploring and applying quantitative tools to examine design protocol in a collaborative virtual environment. After introducing the motivation, a design ontology along with two methods of analysis are depicted as a foundation for this investigation. The case data of a virtual design session is presented which has been examined together with its counterpart face-to-face design session that act as a base-line. In this case the 3D virtual environment slows down the design activities and it also has an inclination to favor certain design activities.**

***Index Terms*—Virtual collaboration, design ontology, protocol analysis, Markov chain, linkography.**

I. Introduction

The concepts and technologies of using collaborative virtual environment have aroused researchers and designers interest since the nineties [1] [2]. However, virtual collaborative design environments, especially 3D, remain mainly in the academic research arena. They are not as popular as those social virtual environment similitudes. We suspect this is due partially to the intention of those environments but also there is a lack of relevant tools to support design activities. On the other hand, our understanding of how tools impact design activities is limited. Over the past three decades, protocol analysis has become one of the most widely used methods to study human design activities and cognitive design processes [3] [4]. Protocol analysis has also been used as a tool to study human behavior in virtual environment e.g. path finding behavior [5] and design behavior [6]. However, there is a lack of uniformity in both the method and coding of protocols when studying design activities. Many coding schemes have been developed are unique to the data. This limits the applicability of the results obtained. There has not been an adequate basis to compare and build on such research to inform virtual environment tool builders to implement an environment for design collaboration. This paper explores the feasibility and applicability of using a generic method and coding scheme, based on an ontology, to study design protocols by comparing two sets of protocol data: a 3D virtual world design session and a face-to-face design session.

II. FBS Ontology

The FBS ontology [7] models design process in terms of three fundamental classes of variables: function, behavior, and structure; along with two external classes: design descriptions

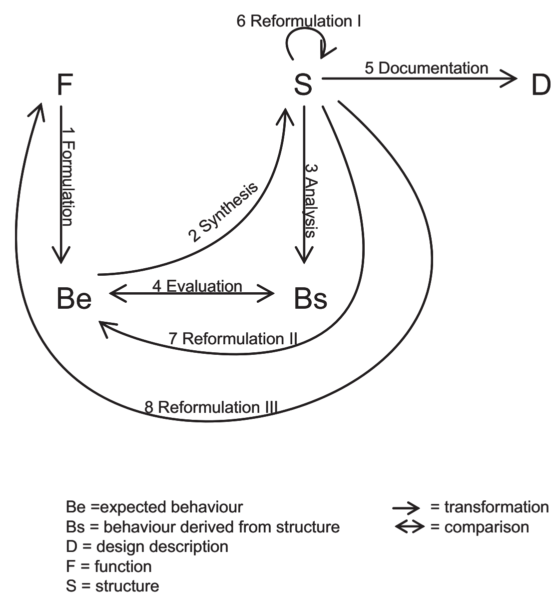


Fig. 1. The FBS ontology of design processes

and requirements. In this view the goal of designing is to transform a set of functions into a set of design descriptions. The function (F) of a designed object is defined as its teleology; the behavior (B) of that object is either expected (Be) or derived (Bs) from the structure (S) that is the components of an object and their relationships. A design description cannot be transformed directly from the functions, which undergo a series of processes among the FBS variables. Figure 1 shows the relationship among those processes and variables. The eight processes: 1) formulation, 2) synthesis, 3) analysis, 4) evaluation, 5) documentation and 6-8) three types of reformualtions, are claimed to be the foundation of all design processes.

A. Generic Ontological Coding Scheme

The generic coding scheme consists only of the function (F), expected behavior (Be), behavior derived from structure (Bs), structure (S), documentation (D) and requirement (R) code categories. The protocols are segmented strictly according to these six categories. Those protocols, utterances, that do not fall into these categories will not be considered nor coded; these may include jokes, social communication, management, etc. Examples of these codings are given in Fig. 2 and Table I in Section IV. These fundamental FBS classes denote the state of affairs of designing of each coded segments. We anticipate this will capture the essence of design activities. Unlike many other complex coding schemes, which processes are being coded, this simple ontological coding scheme provides the foundation for further analysis. The eight design processes will be investigated by Markov analysis and linkography as proposed in the following subsections.

B. Transformation Processes: First Order Markov Chains

Markov chains, also referred to as Markov analysis, examines the sequence of events; they analyze or describe the probability of one event leading to another. In mathematics, a Markov chain is a discrete-time stochastic process with a number of states such that the next state solely depends on the present state. In the protocol analysis of design activities, McNeill et al. [8] treated analysis, synthesis and evaluation as Markov states. They found that the most likely event to follow analysis is a synthesis event. Also the most likely event after synthesis is an evaluation event but the most likely event after an evaluation event is a synthesis event.

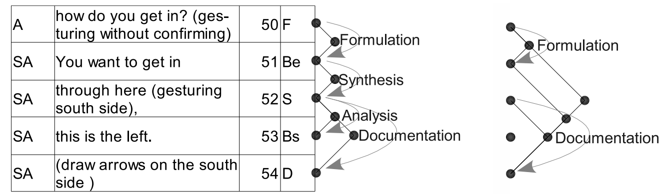
In this paper, each coded segment is considered as an event of a Markov state. A 6x6 (the six code categories) transition or probability matrix is used to describe the FBS Markov chain, as in (1), with which each row summing to one. P_{ij} is the probability of one state leading to another. For example P_{FBe} is the probability of having a Be event after an F event. This transition is likely to be a formulation process.

$$P = \left(\begin{array}{c|cccccc} & R & F & Be & Bs & S & D \\ \hline R & P_{RR} & P_{RF} & P_{RBe} & P_{RBs} & P_{RS} & P_{RD} \\ F & P_{FR} & P_{FF} & P_{FBe} & P_{FBs} & P_{FS} & P_{FD} \\ Be & P_{BeR} & P_{BeF} & P_{BeBe} & P_{BeBs} & P_{BeS} & P_{BeD} \\ Bs & P_{BsR} & P_{BsF} & P_{BsBe} & P_{BsBs} & P_{BsS} & P_{BsD} \\ S & P_{SR} & P_{SF} & P_{SBe} & P_{SBs} & P_{SS} & P_{SD} \\ D & P_{DR} & P_{DF} & P_{DBe} & P_{DBs} & P_{DS} & P_{DD} \end{array} \right) \tag{1}$$

C. Transformation Processes: Linkography

Linkography was first introduced to protocol analysis by Goldschmidt [9] to assess the design productivity of designers. The design protocol is decomposed into small units called "design moves". Goldschmidt defined a design move as "a step, an act, an operation, which transforms the design situation relative to the state in which it was prior to that move" [10]. A linkograph is then constructed by linking related moves. The links are established by discerning, using domain knowledge and common sense, whether a move is connected to the previous moves. The design process can then be examined in terms of the patterns of move associations.

The first order Markov only considers the intermediate step but not the previous ideas. We expect that by constructing a linkograph, connecting related segments, we will be able to capture the design processes in more detail. Fig. 2(a) shows the annotated coded protocol together with its linkograph. The first column records the participants, "A" represents the architect



(a) Human constructed

(b) WordNet generated

Fig. 2. FBS processes derived from linkograph

and "SA" represents the senior architect. The second column contains the verbal protocol together with the annotations in brackets. The third column is the segment number and the fourth column contains the code. The dots represent the segments and the links and the gray arrow lines represent the derived FBS processes. The four links represent four FBS processes. Segment 52 has two links, which indicate it spawns two processes: analysis (S to Bs) and documentation (S to D). This documentation process will not be picked up by the first order Markov analysis.

Linkography has been criticized for the lack of objectivity in the construction of links, which primarily based on the discernment and interpretation of the analysts. Also, the process of constructing a linkograph is very time consuming and cognitively demanding, making it difficult and impractical to study and compare large data set [11]. Some analysts utilize the search function to help finding "moves" with similar semantic contents [12]. We proposed to automate the construction of linkographs by connecting "moves" using a English lexical database, WordNet [13]. WordNet uses the concept of cognitive synonym (synset) to group words into sets. Words within a synset are connected by meaning. Synsets are also interlinked by means of conceptual-semantic and lexical relations. A program was written to generate the links from the annotated and segmented protocol, column two of Fig. 2(a). The program also produces four links, Fig. 2(b). Of the four connections that WordNet finds, only two of them are considered to be legitimate FBS processes. Not withstanding the differences, it picks up the "documentation" process that Markov analysis leaves out. In this paper we explore the WordNet generated linkographs and use it to complement the Markov analysis of the two sessions.

III. DATA: TWO DESIGN SESSIONS

This case study contains two sets of *in-vitro* architectural design sessions are used. The participants remain the same in both session so as the complexity of the design task. They were asked to collaborate in two different environments and each session lasted for 30 minutes, which was video recorded. The participants consist of a senior architect and an architect and they are from the same company. Below are a concise summary of the qualitative analysis of the two sessions.

1) Face-to-face Design Session: In this experiment the designers were asked to design a university student union's gallery. The senior architect took the leadership role, made most of the decisions, and did most of the sketches. This session can be divided into four stages or episodes, based on the design activities. In the first episode they dealt with the brief and site (about 3.5 minutes). In the second episode they analyzed, planned and developed concepts in the plan (about 9 minutes); issues like location of main entrance and service entrance, icon to capture attention were discussed. In the third episode they developed the 3D form in elevation (about 9 minutes); ideas like "ribbon", "hole in the middle" were suggested. In the final episode they worked on the layout, calculated the required areas, in the plan until the end (about 8.5 minutes), but they did not finish it within the 30 minutes allocated for the session.

2) 3D Virtual World Design Session: A customized Active Worlds, an avatar-based multi-user virtual environment (http://awportals.com/), was used in this experiment. The design tasks were to generate conceptual designs and dance studio. Both participants received prior training of using the environment. The senior architect organized most of the activities. The stages were not as well defined as in the face-to-face session; they spent less than 2 minutes with the brief before exploring and making objects. This session can be characterized as "designing through making". Sometimes they subdivided the tasks and worked individually. They were given predefined elements—space, slab, wall, column, and beam—in various sizes. They decided to start with the biggest space element to represent the "largest" spaces, the four studios. At around 12 minutes, they discovered they could not have all the studios on one level because of the site coverage constraint. The senior architect decided to stack the blocks, the studios, and create an atrium to join them together. They tried to further develop this concept to accommodate the requirements but did not finish the design. Besides designing, time was spent on design support activities, such as discussing what elements were available and organizing what to do. Also, time was spent on the technical aspects of learning how to do things, such as changing the color of the blocks, how to "fly", and how get out when "trapped inside" those blocks.

IV. Coding and Results

Table I shows examples of segments from the two design sessions in relation to the coding categories. In this exploratory case, only the first 11 minutes were coded, when they finished the first sheet of drawing. The coding was self arbitrated with over 90% agreement. In another study of over 1,000 segments, the intercoder agreement with the arbitrated set was about 90% and the inter-coder agreement was about 80%. The biggest disagreement appeared in the Be and Bs code. Out of the 205 segments in the face-to-face session, 192 of them contain FBS code. The virtual world session contains 155 segments and 94 of them have FBS codes. Table II documents the frequency and distribution of codes of the two sessions. Fig. 3 shows the percentage distribution of the FBS codes, only consider those segments with FBS codes. Chi-tests reveal that the FBS frequency distribution of the codes does not bear any relation.

TABLE I
Examples of coding from the sessions

Code	Face-to-face	3D World
R	(read brief) "Permanent collection is 200 and 50 meter hanging space."	"They want four studio's mate, two one hundred each."
F	"hang on, thats a public building."	"If it's a dance school it might still need a loading space."
Be	"Can we say this is sort of external?"	"We need to, the obvious thing we've got... the generic space..."
Bs	"So these guys are coming across, they will be coming across this side."	"that's very small area, court yard terrace and rough space maybe undefined,"
S	"This is the Guggenheim"	"I don't know what size they are."
D	(draw arrows) (sketch)	(insert box) (move box)
Not Coded	"How long do we have for this exercise?"	"I can't see you though"

TABLE II
Frequency and percentage of codes

Code	Face-to-face	3D World
R	16 (8%)	7 (5%)
F	19 (9%)	2 (1%)
Be	32 (16%)	5 (3%)
Bs	25 (12%)	7 (5%)
S	65 (32%)	53 (34%)
D	35 (17%)	20 (13%)
Not Coded	13 (6%)	61 (39%)
Total	205 (100%)	155 (100%)

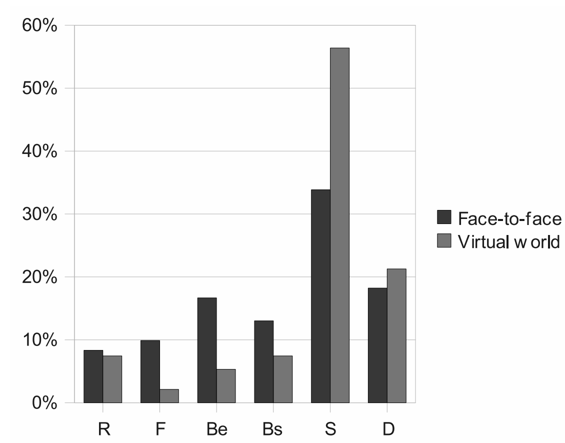


Fig. 3. Percentage distrbution of FBS codes

The overall segment per minute of the face-to-face and the virtual world sessions are 18.6 and 14.1 respectively. This approximately detonates the speed of activities. The FBS segment per minute of the face-to-face and the virtual world sessions are 17.5 and 8.5 respectively. This is a rough indication of the rate of design activities, which indicates the face-to-face is designing two times faster than the virtual world session.

A. Markov Transition of the Sessions

Equation (2) and (3) show the transition matrix of the two sessions with the subscripts *f2f*, and *3D* represent the face-to-face and virtual world session respectively. If we rank the probabilities, the highest is the F to Be in the 3D session that is 1.00. This mean whenever there is an F event a Be event will follow. This transition represents the formulation process, assuming most of the consecutive events were related. Both the Be to S and S to S are 0.60. The Be to S probability can be seen as the probability of a synthesis process when an Be event occurs. Similarity, the S to S transition probability can be seen as type 1 reformulation probability when an S event occurs. The type 2 reformulation is lower than type 1 reformulation in the two sessions. Type 3 reformulations are very rare. The probability of a analysis process from a S state (S to Bs) is surprisingly low in the virtual world session. Fig. 4 shows the probability of the eight FBS processes, as depicted in Fig. 1, triggered by the FBS events of the two sessions. For the evaluation process, we added the Bs to Be and Be to Bs transition probabilities. The distribution of the probabilities of the FBS processes of the two session looks very different.

$$P_{f2f} = \left(\begin{array}{c|cccccc} & R & F & Be & Bs & S & D \\ \hline R & 0 & 0 & 0.40 & 0 & 0.40 & 0.20 \\ F & 0 & 0.18 & 0.45 & 0 & 0.27 & 0.09 \\ Be & 0 & 0.08 & 0 & 0.04 & 0.20 & 0.68 \\ Bs & 0.12 & 0 & 0.35 & 0.24 & 0.18 & 0.12 \\ S & 0.02 & 0.04 & 0.15 & 0.10 & 0.46 & 0.23 \\ D & 0.06 & 0.15 & 0.15 & 0.18 & 0.42 & 0.03 \end{array}\right) \quad (2)$$

$$P_{3D} = \left(\begin{array}{c|cccccc} & R & F & Be & Bs & S & D \\ \hline R & 0.14 & 0 & 0 & 0.43 & 0.43 & 0 \\ F & 0 & 0 & 1.00 & 0 & 0 & 0 \\ Be & 0 & 0 & 0 & 0 & 0.60 & 0.40 \\ Bs & 0.43 & 0 & 0 & 0 & 0.43 & 0.14 \\ S & 0.04 & 0.02 & 0.02 & 0.06 & 0.60 & 0.27 \\ D & 0 & 0.05 & 0.10 & 0.05 & 0.65 & 0.15 \end{array}\right) \quad (3)$$

1) Mean First Passage Times of the Sessions: The mean first passage time is the average number of steps traversed before reaching a state from other states. The mean passage time can be obtained from the transition matrix [14]. Equation (4) and (5) show the mean first passage matrices of the two sessions. The longest mean passage time is from R to F (59.66) in the virtual world session and the shortest is from D to S (1.96) also in the virtual world session. The average mean

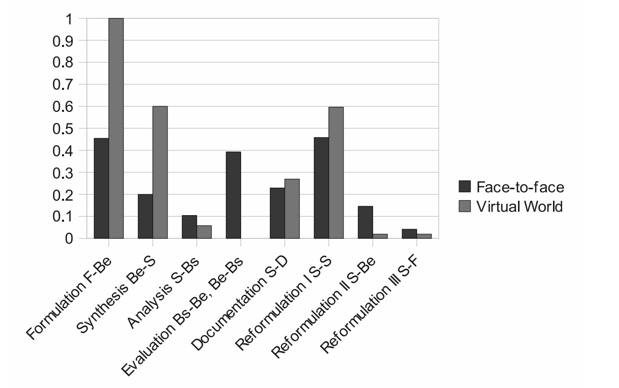


Fig. 4. The probability of the FBS design processes triggered by the FBS events

passage time of the face-to-face session and the virtual world session are 14.72 and 21.06 respectively. The minimum of this average occurs when all the events are evenly distributed, that is the transition probabilities are all equal. The virtual world session is comparatively more disproportionate. It has a fast occurrence of *structure* (the column of S in (5)) and slow occurrence of *function* (the column of F in (5)). The face-to-face session has also a fast occurrence of *structure* but the slowest occurrence is *requirement* (the column of S and R in (4)).

$$M_{f2f} = \left(\begin{array}{c|cccccc} & R & F & Be & Bs & S & D \\ \hline R & 49.96 & 16.85 & 5.38 & 10.86 & 3.24 & 4.07 \\ F & 50.32 & 14.23 & 4.86 & 11.19 & 3.74 & 4.39 \\ Be & 49.35 & 15.48 & 7.06 & 10.19 & 3.73 & 2.95 \\ Bs & 46.11 & 17.21 & 5.24 & 8.68 & 4.09 & 4.42 \\ S & 49.03 & 16.54 & 6.54 & 9.80 & 3.05 & 4.33 \\ D & 48.05 & 15.22 & 6.15 & 9.32 & 3.27 & 5.02 \end{array}\right) \quad (4)$$

$$M_{3D} = \left(\begin{array}{c|cccccc} & R & F & Be & Bs & S & D \\ \hline R & 23.04 & 59.66 & 22.54 & 9.35 & 2.58 & 6.11 \\ F & 31.21 & 59.15 & 3.64 & 18.46 & 2.97 & 4.70 \\ Be & 30.21 & 58.15 & 20.85 & 17.46 & 1.97 & 3.70 \\ Bs & 20.42 & 59.33 & 22.16 & 14.37 & 2.51 & 5.52 \\ S & 28.81 & 57.65 & 20.58 & 16.26 & 2.05 & 4.37 \\ D & 29.80 & 56.40 & 18.75 & 16.76 & 1.96 & 4.75 \end{array}\right) \quad (5)$$

B. Semantic Linkographs of the Sessions

WordNet finds 4,261 and 2,929 links in the face-to-face and the virtual world sessions respectively and their corresponding average links per segment, also called link index, are 20.79 and 18.90. From experience, these figures are ten times higher than the human constructed linkograph.

Table III shows the number of links that are considered to be legitimate FBS processes. The percentages are in brackets. The virtual world session has much higher non-legitimate FBS links. Also, it has a much higher percentage of S to S links. Fig. 5 group those processes into the eight FBS processes.

TABLE III
NUMBER AND PERCENTAGES OF FBS PROCESSES DERIVED FROM WORDNET

Links	Face-to-face	3D World
R-F	45 (2.37%)	8 (1.11%)
F-Be	65 (3.42%)	2 (0.28%)
Be-S	269 (14.16%)	21 (2.92%)
S-Bs	178 (9.37%)	34 (4.73%)
Be-Bs	79 (4.16%)	1 (0.14%)
Bs-Be	101 (5.32%)	7 (0.97%)
S-D	238 (12.53%)	25 (3.48%)
S-S	562 (29.58%)	542 (75.38%)
S-Be	200 (10.53%)	46 (6.40%)
S-F	163 (8.58%)	33 (4.59%)
Others	2361	2210
Total FBS	1900 (100%)	719 (100%)
Total	4261	2929

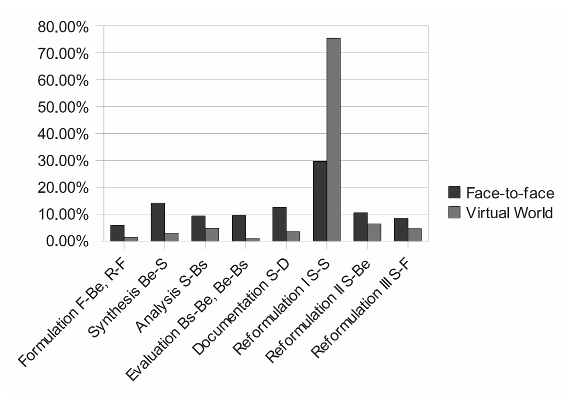


Fig. 5. The percentages of FBS design processes derived from WordNet

The virtual world session is not only predominantly biased towards *structure* related activities, but 75.38 % are *structure* to *structure* activities. Evaluation activates are rare (1.11%) so are the formulation activates (1.39%). This maps well with our observation of "designing through making" as depicted in Section III.

Comparatively, the face-to-face session has higher percentages of all the FBS processes except for the type I reformulation (S to S). The face-to-face also has a high percentage of *structure* to *structure* activities (29.58%), followed by synthesis (14.16%) and documentation (12.53%). Formulation has the lowest percentage (5.79%). The percentage of other processes ranges between 8.5% to 10.6%. The result is also consistence with our observations and qualitative analysis of the first and second episodes briefly mentioned in Section III.

V. DISCUSSION AND CONCLUSION

The processes from the FBS ontology are claimed to be generic for all designing. Unlike most coding schemes that allow overlapping of codes, the ontological approach requires precise discernment of one code per segment. This clear distinction converts the protocol into unambiguous segments; it quantifies the amount of effort spent in relation to function, behavior, or structure, which facilitates the comparison. This simple ontological coding scheme opens up the possibility to study designing using the same foundation. Hence, different sets of data can be compared and cross validated.

Markov analysis of the FBS events provides a way to examine design protocol data in a sequential manner. It does not assume that successive events are independent. The transition matrix can be viewed as a signature that summarizes the transitions between all the FBS events. These transitions can provide a rough idea of the distributions of the eight FBS processes by assuming that high percentages of the consecutive segments indicate a direct relation. Comparing these processes informs us of the characteristics of a session. The mean first passage time matrix provides another view of the design process in terms of the expectancy of FBS events. This gives us a feel of the importance of a state.

The links and FBS processes derived from WordNet linkographs are much higher than human constructed linkographs. However, the distribution of FBS processes are consistence with our qualitative analysis. Further studies are required to validated the use of WordNet generated linkographs.

In this case study the speed of meaningful communication exchange, number of FBS segments over time, is much higher in the face-to-face baseline session (17.5 against 8.5). This speed in some way reflects the rate of design cognition. The most possible explanation is that there is a cognitive resources overhead in using the virtual environment. The transition and mean passage times matrices show the virtual world session was biased toward *structure* related transitions. The WordNet derived FBS processes also confirmed that. This shows the virtual world environment imposed partiality for *structural* activities. The FBS processes derived from WordNet generated linkographs echo the finding of the Markov analysis; over 75% of the FBS processes are *structure* to *structure*.

This case study also successfully shows the usefulness of the generic coding scheme. The results from the two analysis not only match our observations and qualitative analysis but also provide further insight into the design activities quantitatively.

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