Synthetic Environment as a Communication Tool for Dynamic Prototyping

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Abstract: *Synthetic environment equipped with user interfaces intuitive for direct 3D shape modification by non-designer stake-holders was proposed as a collaboration tool for design concept communication in dynamic prototyping of product design in early stages of the design process. After a survey of 3D user interaction techniques for SE, a simple user interface with hierarchical visual menu was proposed and a proof-of-concept implementation of it was tested to be intuitive with experiment, which serves as a base for further study to verify the hypothetical benefits of SE aided dynamic prototyping in terms of communication efficiency and accuracy.*

1. Introduction

A Synthetic Environments (SE) is an artificial environment for simulation of its real world counterpart. As a general term, SE refers to a superset concept of environments constructed with Virtual Reality (VR), Mixed Reality, teleoperation or telerobotics technology [1]. The SE in the research scope of this paper is limited to the application domain of Industrial Design, especially in the early stages of the design process like the conceptual design phase where the SE is believed to have wider margin of advantages.

There have been many successful VR application systems in military, medical, mechanical industry and scientific research, as reviewed by [1][2] [3][4][5][6].

With the evolution of VR technologies from the objects of scientific research into industrial engineering practices and products, they were transferred from academic and research realm into high-tech and further industrial and business sectors. This development shed light on manifold applications of VR technologies, including SE for industrial design to solve existing problems, improve the current solutions, provide new avenues to old targets and inspire innovative requirements.

One of the commonly accepted major benefits of SE is the feasibility of prototyping with relatively low-cost virtual or mixed reality prototype compared to the conventional physical prototype. A prototype in an SE provides instant feedback to speed up the iterative design process.

SEs were already applied to support the prototyping of vehicles [7], the design on a virtual workbench [8], production planning [9][10], and haptic virtual product assembly [11], etc. Jimeno and Puerta's [12] presented a recent overview of VR applications in design and manufacturing. Cecil and Kanchanapiboon's survey [13] provided a comprehensive review on virtual prototyping (VP). However, most of these applications are targeted at the later stages of the product design process to provide dynamic simulation of the relatively matured prototypes of products.

For earlier stages of produc design, Antonya and Talaba [14] presented recently one of the first VR applications for product analysis stages. Bordegoni and Cugini [15] demonstrated a possible application in the conceptual stage, using haptic clay modelling. The research work of this paper is also an attempt to explore the problems and solutions of SEs as a collaborative dynamic prototyping facility for early stages of the design process, especially the concept design phase.

Beyond the currently common practice of using SE as a presentation and demonstration facility, there are articulated demands of on-the-spot modification support for dynamic prototyping. To seek solutions for these requirements, easy interaction interface to 3D shape modification tools are discussed.

Although there are plenty of researches done to provide support of 3D model modification in Virtual Environments (VE), most of them targeted at using VR as an intuitive interface to conventional CAD systems. They're either concentrated on 3D interaction techniques for navigation in 3D virtual world, or closer simulation of the real world senses based on the implicit assumption that thus it can be intuitive because the user lives in and interacts with the real world. Another common feature of these researches is that they tried to provide shape modification in a VR style, but mostly only the designers were taken into account. These can be seen from the discussions about 3D interaction techniques below.

But VR is not necessarily the intuitive way of interaction. Rather, intuitiveness is a question in VR itself for users with different knowledge backgrounds. We consider SE from the communication point of view. No wonder the concept of VR originated as a "Man-Machine Graphical Communication System" [16]. These problems are discussed and our solutions are proposed, i.e. intuitive user interface (IUI) for product design concept communication purposes, especially 3D shape modification as a communication tool between different stakeholders involved in a user-centered design process. Further research on adaptable scenario modification is also discussed briefly.

2. SE Aided Dynamic Prototyping

Prototyping refers to the design process of making mock-ups of the product for testing and evaluation purposes. In most of the cases the costs of physical prototypes are relatively high so a digital virtual prototype is preferred thus the designer can modify the prototype with lower costs than a physical prototype. Moreover, the prototyping process may also employ physical and/or virtual prototype, with 3D scanning and rapid prototype manufacturing (such as stereo lithographic 3D printing) techniques to support seamless modification migration, or with Augmented Reality (AR) to impose virtual modifications on physical prototypes [17][18]. Such a process is called Dynamic Prototyping (DP).

Fig. 1 illustrates a DP process aided by SE. The designers present their design of the product through a prototype in the SE to the product end users (and other stakeholders), and the users test the product design by interacting with the prototype in the SE and comment to the designers by direct modification on the prototype. The consequences of the desired

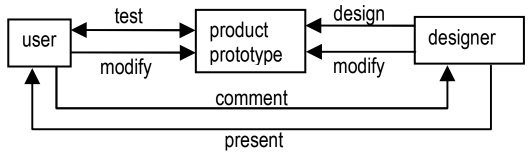

Fig. 1 *Dynamic Prototyping in Synthetic Environment*

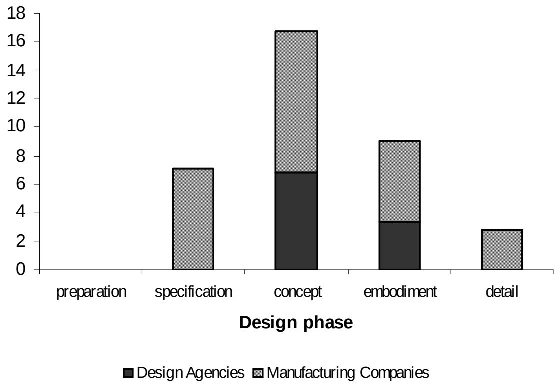

Fig. 2 *Application phase preferences; scores normalized to total number of answers*

modifications can be visualized and simulated instantly. The major enhancement of such a DP process to the conventional design process is closer involvement of the end users and other non-designer stakeholders in the design process.

One example of the virtual DP research reported by Niesen [19] in 1999 was a mixed reality environment for vehicle operator interface design. It included an industrial robot, force feedback joysticks, levers and other control hardware components in conjunction with graphics to create an environment which can be readily reconfigured and tested without lengthy design changes.

User Interview

We conducted group interviews with a group of experienced designers and engineers (including experts from the product designer and manufacturer companies) to collect subjective evaluation of applicability of SE in a product design process. In these interview sessions, first the participants got an experience in a sample SE system by operating it. Then, some haptic parameters of the prototype in SE were adjusted according to their desire to provide them a basic idea of the feasibility of DP in SE.

After that, they were asked to compare this with their current work practice and propose the possible applicability of such an SE in the product design process. A semi-structured approach was adopted, which enabled the participants to produce unlimited feedback.

One of the interesting information we got from the interviews were the deemed applicability of SE to different phases of product design process, as shown in Fig. 2. About 47% (17 out of 36) participants perceived the SE to be applicable to the concept design phase, in contrast to 25% (9 out of 36) for the embodiment design phase, 19% (7 out of 36) for the specification and requirement definition phase, 8% (3 out of 36) for the detail design phase. This showed high level of acceptance in the designers and engineers user group on SE application in the concept design phase.

Another important feedback is from the designers group: “Leave creativity with designers”. It’s not a common practice so they won’t expect the users to provide design solutions in the design process. Normally the users only provide requirements. Nevertheless, the applicability of an SE aided DP process to help design concept communication was recognized and desirable. For example, normally it’s difficult to imagine the designed force feedback or to describe the desired force feedback of the machine lid without instant tuning and testing of the dynamic prototype in the SE. This empirical statement is in accord with our discussion in section 3 regarding the SE as a communication tool between different stakeholders with different knowledge and skills.

In Brooks’ review [20] of VR application systems, he observed the following industrial application requirements: “The most strongly desired tools are geometry manipulation tools, ways of easily specifying interactions with the design. … The great desire is for interfaces simple enough for the occasional user to participate in model changing.”

The above means the inclusion of non-designer roles in the DP process is desirable, which we perceive as requirements of both a supporting framework of process integration, as well as intuitive user interfaces for occasional users. Because of this, SE for product design will be discussed regarding potential benefits as a communication tool with intuitive user interface to support user-centred dynamic prototyping.

3. SE as a Communication Tool

In Biocca and Levy’s book [21], VR was investigated as a communication media in the general sense. It allows the presentation of design information in a way that it is comprehendible regardless of discipline or training. The consequences of design choices can be experienced rather than imagined. Here the SE served as a collaborative workspace for designers.

Because the different roles in the product development process have different knowledge backgrounds and different levels of expertise, which is an intrinsic problem regarding the multi-disciplinary characteristic of industrial design, obstacles in communication of requirements and design concepts are often the causes of delayed, faulty, mismatched, inferior, or even failed products.

One of the possible benefits of SE to product design process is to provide low-cost prototyping methods to speed up design evaluation feedback loops and to achieve optimization of the product design by enhancing communication in the design process including all the stake-holders of different roles like customers (product end users), marketing personnel, designers, engineers, business management personnel, etc.

Especially at the earlier stages of the product design process, such as the conceptual design phase, normally both the design concepts and the available prototype is uncertain and ambiguous. The requirements and solutions are general, vague and conceptual rather than accurate, concrete and specific, which is hard to communicate without help of intuitive models. High impact changes are still under consideration thus intensive communication of design concepts are critical for decision making among the different stakeholders of the product development group.

When SE is studied on the application background of industrial product design, it includes not only theories and techniques about virtual or mixed-reality simulation of objects, but also those about accessibility of the technologies by the human users who interact with them, specifically, all the stakeholders participating in the product design and development process. Such an SE must be simple in configuration, non-obstructive to the design process and accessible to all stakeholders without specialized training.

Cruz-Neira et al. (1992) [22] stated in bold characters in their report of the CAVE system, that “One of the most important aspects of visualization is communication. For virtual reality to become an effective and complete visualization tool, it must permit more than one user in the same environment.” This means that the communication feasibility is not only a merit provided by a VE or in our case, an SE, but also an indispensable component of the SE to make it “effective and complete”.

Likewise, we also regard the SE as a tool for communication of concepts and ideas, for either traditional prototype evaluation, or collaborative, interactive user-centred dynamic prototyping. The simulation of the product is one-way communication to present the product information to the stakeholders. Intuitive interaction methods without intrusion into the communication are promising to break the obstacles in the other direction to ease the expression of modifications of complex product features requested by different roles, in addition to traditional verbal and sketch drawing approaches. So we need to consider the intuitiveness of user interaction in SE from a communication point of view.

Adaptable Scenario

Recently, the product design process is undertaking a gradual transform from the traditional problem solving activity in which the result is determined by a series of technical decisions, to the new paradigm as a group activity centralized on communication and collaboration between all the stake holders. Together with this development of design philosophy comes the concept of Scenario Based Design (SBD), with which the non-designer roles can also be proactive in the design process. A scenario can be defined as a sequence of events within a certain context. The SBD approach provides insight into the possible consequences of a specific decision by using scenarios in product design process to explicitly show and address problems, needs, constraints and solutions [23].

Normally for certain prototype in SE, the usage scenario is pre-defined by the designer of the prototype and can not be modified easily. Tideman et al proposed an SBD approach in which a set of pre-defined scenarios were provided by the designer for the user to experience in VEs and make their own choices out of it [23][24]. While certain flexibility was provided for the user to reconfigure the scenarios, each of the scenarios themselves is still fixed.

Dynamic Prototyping brings about a new problem. When the prototype is modified, the working mechanism and/or the usage scenario of the product might also be changed. If the SE can support Adaptable Scenario through an intuitive user interface, it may further enhance the design concept communication.

As a related topic, there are already some research done in computer gaming industry for user customizable games [25][26]. An adaptable scenario can be implemented with the help of Computer Aided Software Engineering (CASE) tools and game scenario user customization techniques. New research approach for VR might emerge by borrowing methods from the computer game industry, and vice versa [27].

Furthermore, any specific virtual prototype is designed for certain usage scenarios. The instant modification of the prototype often causes instant change of usage scenarios. Or inversely, the changes of usage scenarios themselves come first as user requirements and the modification on the product prototype is provided as a solution.

4. Intuitive User Interface for Dynamic Prototyping

4.1. 3D User Interaction

Researchers are trying in various approaches to improve the 3D user interaction techniques in SE with:

a. Hardware innovation: 3D pointers, motion tracking, haptic device, etc.

Among the 3D input hardware advancements, SensAble Technologies is most successful in bringing haptic device into 3D touch-enabled desktop modeling systems. Murakami and Nakajima (2000) [28] designed a new deformable device as 3D input hardware.

b. New handles and metaphors

A lot of researches have been done in intuitive input methods, such as gesture, hand motion as well as voice command. One of the many examples is the work Nancy Diniz (2003) [29] did in study of free hand 3D form generation in VE. H. Lipson et al. (2000) [30] and R. O. Buchal (2002) [31] among many other researchers studied methods for reconstruction of 3D shapes from free hand sketches. Chu et al [32] tried to make the UI intuitive by integrating multi-model input methods, such as voice command input and hand motion input with 3D visual output and auditory output.

Frank Steinicke et al. (2007) [33] reported an autostereoscopic display environments in combination with 3D desktop devices that enable users to experience virtual environments more immersive without annoying devices. They proposed an interscopic display environment with implicated user interface strategies that allow displaying and interacting with both 2D and 3D elements. With their interaction strategies [34] for minimal instrumentation that can be integrated easily in everyday working environments, mouse, keyboard and stereoscopic elements like gesture-based input coexist in complement of each other. Similar to our research, they aim at a minimal necessary setup for small to medium business (SMB) industrial design applications.

c. Better mapping strategy to 2D space

Vivek Vaidya et al. (2007) [35] also applied the strategy of making 2D user interfaces viable within 3D VE. Feiner, S. K. and Beshers, C. (1990) [36] suggested a technique to enable interaction with higher dimentional space with lower dimentional devices. This is a useful technique also applicable for effective manipulation of 3D shapes with 2D interface.

Ji-Young Oh et al. (2006) [37] reported a 3D concept design system SESAME supporting sketching in 2D space.

d. Better organization of the components and functions

Raimund Dachselt and Anett Hubner (2007) [38] published a survey of different types of 3D menu that applied in VR and MR systems.

Bærentsen's [39] research studied on a metaphorical description approach of IUI design. Though the example case is for a TV menu system, the basic principles of intuitive cognitive functions and natural behavioral tendencies still apply in our case.

Problems

Just as Bowman and Frohlich [40] stated in their 2005 review paper of the trend history of 3D UI research and analysis of the current state-of-the-art, "very few fundamentally new techniques and metaphors for 3D interaction have been discovered in recent years, yet the usability of 3D UIs in real-world applications is still not at a desirable level." The authors suggested that the directions for future 3D UI research should be centered around:

a) Increasing specificity in 3D UI design;
b) Adding, modifying, or tweaking 3D interaction techniques to produce flavors
c) Understanding the integration of 3D interaction techniques
d) Addressing the implementation issues in 3D UIs
e) Applying 3D UIs to emerging technologies

4.2. Intuitive User Interface for SE

Most of the researches on SE user interface were based on one of the following assumptions:

a. The SE itself is a more intuitive user interface for most users, thus most of the researches focused on application of SE as an intuitive interface to certain tasks.

b. 3D user interaction techniques should be improved to simulate the real world activities the closer the better to be intuitive to the user. This led to efforts to provide higher level of immersion and presence.

There were quite some research projects that applied VR technology to provide intuitive user interface to current CAD software. Eg. Mark Taylor et al. (2007) [41] presented an evaluation of a VR based UI for a software environment called INTEGRA, which supports collaborative working during conceptual design of houses. A virtual interactive collaborative environment (VICE) UI was described to facilitate the intuitive usage of highly complex systems, which may only be used on an occasional basis.

But these are not always true for all application cases. As Bowman (1995) and Willans (2001) pointed out, even virtual environments which contain moderately complex interaction techniques suffer problems which are not simply solved by more realistic modeling of real world techniques. "An interaction technique which is highly usable in one context is likely to be less usable within another" [44]. According to Bowman (1999), even when there is a real world equivalent, usability reports have shown that techniques 'closer to natural mapping often exhibit serious usability problems' [45]. Especially for industrial design engineering tasks, the efforts needed in deployment of an SE in the design process might be an obstacle preventing the designers and engineers from working effectively within the high immersive VE. Furthermore, the intuitive interaction techniques for the purpose of highly immersive 3D VR experience may block the design concept communication when it doesn't fit the conventional work flow.

At the early stages of the design process, such as the conceptual design phase, normally both the design concepts and the available prototype is not accurate. Furthermore, in our user survey study [42], many designers also expressed the opinion that they don't expect the customers to provide design solutions. The task of the customers is normally to provide the requirements. Before solutions were defined, these requirements are general, vague and conceptual rather than accurate, concrete specifications.

On the other hand, professional CAD user interfaces which can manipulate the product model in an accurate way normally requires certain level of training before the user can operate them at will without interrupting the design concept formation and communication. Reversely, intuitive user interfaces normally can't provide handles for highly accurate design modification.

To solve this problem, Nassima Ouramdane et al. (2006) [43] suggested splitting the VE space into three zones in which a specific interaction model is used: a free manipulation zone, a scaled manipulation zone and a precise manipulation zone. In the free manipulation zone, rough intuitive operation is supported; while in the precise manipulation zone, a more complex but more accurate interface assisted by virtual guides is supported.

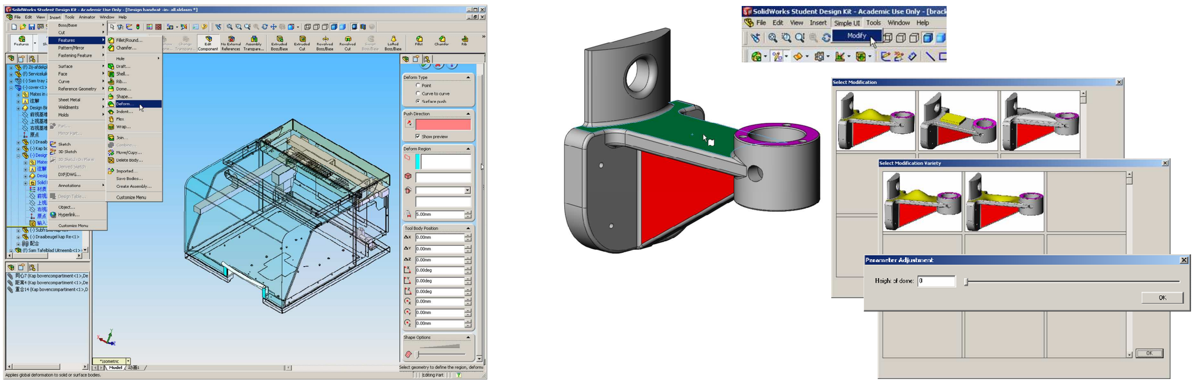

Fig. 3 *left: Original UI* *right: Intuitive UI with visual menu*

4.3. Solution

We propose a different approach to solve the above problems. Since different roles with different backgrounds have different senses of intuition, it's highly possible that one type of intuitive interface for one role turns out to be intricate for another role. For example, the designers may feel difficult to understand or operate with the UI of an engineering software although the engineers feel it quite intuitive. Thus, different roles should be presented with different customized interfaces. Naturally, the designers and engineers feel more comfortable with the CAD software interfaces of their daily use. So in the SE, it should be possible for different roles to manipulate the common product model through different intuitive interfaces of their own choices.

Bowman et al [50] provided some general guidelines for 3D UI design after a detailed overview of the techniques:

a) Consider "magic" interfaces in place of "natural" ones when tasks require productivity and efficiency. Natural interaction should be used when a replication of the physical world is important.
b) Choose interaction techniques based on the requirements of the application – the same set of techniques will not work well in every situation.
c) Limit the required degrees of freedom for input whenever possible, and provide physical or virtual constraints to help guide user input.
d) Take advantage of the increased flexibility afforded by whole-body input, multimodal I/O, and novel input devices, but also give the user structure and support in managing the increased complexity.

Following the above guidelines a) to c), a simple intuitive 2D UI for 3D shape manipulation is proposed. Intuitiveness can be achieved by presenting the 3D shape modification tools needed in DP tasks with context sensitive activation, and providing easy access to these tools with step by step visual guide. The modification tools can be organized in a tree-structured hierarchical catalog customized for different roles of the participants in the design process, presented in a group of palettes filled with a grid of visual display of the resulting shape of the object after modification using respective tools.

In the first level of the tool palette, choices of different types of modification tools are presented, with sample pictures or animations of the modification applied to the current model. After that, more detailed varieties of the selected modification tool were presented. Then, the user can fine-tune the modification parameter using direct number input box or a slider. More preferably, a parameter control handle can be displayed on the model for the user to drag with the mouse pointer to tune the parameter and see the instant consequences of modification.

When the number of modification tools is big, such a UI will have scalability problems that it's difficult for the users to hunt down the desired tool buried in the picture grid. To solve this problem, this interface can be further extended with direct tool retrieval by context sensitive keyword searching or voice commanding based on customized vocabulary of different users.

4.4. Experiment

A demo tool was implemented for proof-of-concept test of the hypothetical solution described above and exploring further possibilities and problems. Experiment with a small user group to evaluate the the demo tool was conducted and some feedback information was gathered for further study.

The experiment was conducted using the popular 3D CAD software SolidWorks. The original SolidWorks CAD software UI and a demo intuitive simple UI is shown in Fig. 3 for comparison. A simple 3D model was modified through interaction with a set of visualized tool selection dialog boxes, using C++ programming through SolidWorks API to manipulate the 3D model.

No.	Sex	Age (3)	Job Background	Skill Level (1)	Task completed easily? (2)	Intuitive?
1	M	30	Engineer	+2	+3	Yes
2	M	40	Academic, CAD	+2	-1	Yes
3	M	40	Academic, Reseaercher of CAD	-2	+2	Yes
4	M	40	Engineer, Electronic	-3	+2	Yes, but still confusing
5	F	30	Designer	+2	+2	Yes, but somewhat confusing in certain steps

(1) Subjective score of skill level of SolidWorks or similar 3D CAD Software.
(2) Subjective score of ability to complete the task with the supplied UI.
(3) Age is roughly in decades.
(4) The scores were scaled as
-3 very negative, -2 negative, -1 slightly negative, 0 neutral/unknown, +1 slightly positive, +2 positive, +3 very positive.

Tab.1. *Questionnaire Results*

Procedures

The test procedures are listed as following:

1. Participants were asked to complete requested tasks in the following steps to test the easiness for them to find a solution:
2. Prepare the Solidworks software with a test model file loaded.
3. Show the participants the illustrative description of a series of predefined 3D shape modification tasks to be performed on the given model. But how to do them is not described.
4. Show the participant where the simple UI root menu is located.
5. Let the participant try the simple UI freely.
6. The user activities were monitored. Notes were taken about difficulties, misunderstandings or intended interaction methods.
7. Ask the participant to fill the questionnaire.

The questionnaire contains the following questions requesting a 7 level scaled answers valued from -3 to 3:

1. How skillful are you with SolidWorks or similar 3D CAD software?
2. Can you complete the task with the menu and dialogs?

Further more, the following open questions were asked:

1. The exact difficulty in using such a UI
2. Job background
3. Is such a software intuitive?
4. Any ideas of improvements?

A small group of 5 participants with various backgrounds (2 engineers, 1 designer, 2 academic researchers) took the test to evaluate the demo tool to provide feedback for further study. The major outputs of the questionnaire are:

a. As shown in Tab. 1, participants with different levels of skills with 3D CAD software could complete the modification tasks with ease. All of them considered the UI intuitive, but 2 of the 5 participants felt somewhat confused by the UI. This shows the basic idea of the UI worked well but needs further improvements.

b. Most participants expected an interaction of

    1. Two illustrations of “change from”, and “change into”
    2. Instant update of change
    3. Clear sign to finish each operation. Proper prompt text, more obvious button or guidance should be provided

c. Most participants felt the interface intuitive, but needed improvements. Some visual menu pictures were still not intuitive enough for understanding.

d. People with different background had different tendency of expectations and understanding of the UI. Eg., Engineers prefer number input directly. Apparently all the users tend to think in the way of their familiar software interface in their suggestions of improvements.

5. Conclusions

Literature study and user interview indicated that synthetic environment may be an applicable medium to support the design concept communication in a user-centered design process incorporating non-designer stakeholders, especially in the concept design phase.

The authors propose that a synthetic environment with simple and intuitive 2D user interface for 3D shape modification might enhance design concept communication in a dynamic prototyping process. This should be verified with further experiment results.

The experiment of a proposed simple UI with customized hierarchical visual menu is verified to work well in a small scale experiment, serving as a base for further study. Further experiments will be carried out to compare the efficiency and accuracy of design concept communication between these pairs of cases:

a. Using the traditional verbal, gesture and sketching approaches, vs. using the intuitive interface to modify the model directly;
b. Using original CAD software interface, vs. using the customized intuitive interface.

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