Investigation of Behaviour Exploration Methods of Articulated Product Concepts in Interactive Sketching Environment

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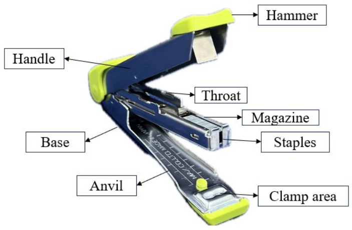
Abstract

In the early stages of conceptual design, there is a heightened mental effort when the designers explore the behaviour of concepts of products with relative motion. Typically, concept generation is carried out using a traditional sketching environment wherein behaviour exploration is largely assisted by mental simulation. The intended behaviour of the concepts is crucial for a successful product idea. This paper presents a novel digital sketching environment that incorporates behaviour exploration of sketches. The software tool Sketching Interface for Mechanism Behaviour Analysis (SIMBA) supports the creation of articulated product concepts with kinematic constraints, which can simulate the behaviour.SIMBA is validated for its utility and usefulness for subjective satisfaction. Further, design experiments were conducted to estimate mental effort and subjective satisfaction. The mental effort involved in explaining the functionality of concepts was estimated Using protocol analysis. It was found that the SIMBA tool helped reduce this mental effort by 77% compared to that of a traditional sketching environment.

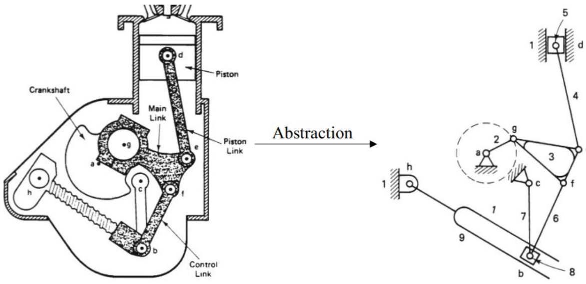
Keywords: Engineering design, Articulation, Functionality, Digital sketching

Article highlights

- Significant mental effort is involved in behaviour exploration of articulated product concepts.



(a) Anatomy of an office stapler



(b) Abstraction of a embodiment product to a skeleton [2]

Fig. 1: Commonly observed articulated products

- A digital sketching interface is developed to address the challenges faced by the designer.
- When the designers used the digital sketching interface, they found it easy, intuitive, and fun to use and expressed their desire to use it.
- The mental effort was also significantly reduced when the designers used a digital sketching interface compared to that of traditional ones.

1 Introduction

A typical engineering design process includes four phases [1] viz., requirements, conceptual design, embodiment design, and detailed design phases. The designers generate concepts in the early stages of design, especially in product/industrial design domains, where designers explore concepts to solve challenging real-life problems through tangible products/devices. In most cases, these product concepts have relative motion between their components. The product concepts, once conceived, go through a series of iterative validation processes to determine their feasibility. These iterative processes are resource-intensive. Thus, reducing the time and effort spent validating the concepts will significantly improve the efficiency of the product development cycle. In the following section, we introduce articulated product concepts and behaviour exploration.

1.1 Articulation in product concepts

Articulation in product design refers to the ability of product subcomponents to move relatively with each other in response to the user's needs and preferences to meet its functionality. This can involve a range of connections between the subcomponents [2], such as hinges, swivels, and sliders, that allow them to change their position and orientation. The kinematic subcomponents and their connections are also called links/rigid bodies and joints, respectively [2]. The components and their connections will be synonymously used as links and joints for the rest of the paper. The base and anvil are considered single parts in the stapler (see Fig 1(a)). The handle can rotate about the base due to the provision of a pivot or revolute joint. This relative motion is considered as articulation.

Articulation is an essential aspect of product design as it can significantly increase the usability and functionality of a product. From now on, the authors will address all the products with articulations as "*articulated product design concepts*."

1.2 Behaviour exploration in articulated product concepts

In product design, behaviour exploration refers to testing and evaluating different design options and variations to optimize a product's performance, functionality, and user experience. There are many types of behaviour in a product, such as thermal, deformations, electrical, etc. Here, in this work, motion is considered behaviour. So, any behaviour exploration implies motion exploration during the conceptual stage of design. In Fig. 1(b) designing a new internal combustion engine, behaviour exploration could involve testing different configurations of the device's joints and links, evaluating the range of motion of each component, and simulating the device's movement and performance in a virtual environment. In behaviour exploration, the embodied structure of the slider-crank mechanism is not required, but a simpler skeleton structure is used. This information is obtained from the *articulations* present in the product. Hence, it can be used to optimize the design and improve the final product's performance. The goal of behaviour exploration is to optimize the performance and functionality of the final product.

1.3 Research gap

In conventional product sketching situations, it can be seen that sketching strokes are created in random sequences. The level of detail is in line with the local information density [3]. A product concept is sketched as an articulated system wherein articulations are either embodied or annotated and have information on the relation between the components and input-output motions. Once the product is sketched, the designers face the challenge of mentally simulating it accurately. If the relative motion between the components is simple, i.e. rotation and translational, motion visualization is easy. It is difficult to visualize if the relative motion is complex, i.e. if it is not rotational nor translational (for example, elliptic motion). The situation gets complicated as the number of components increases. These sketching scenarios have been observed to bring out its characteristics. Based on these observations, the sketching activity's aspects were used in the digital sketching environment as well so that the naturality of the sketching action is not missed.

A sketching environment should facilitate freestyle stroke generation and concept validation through the phases of perception, cognition, and simulation that aid in reducing the complexity of the cognitive process in sketch understanding [3]. For behaviour exploration requirements, typically, the designer has to send the generated concept sketches to a computer-aided design (CAD) platform for modelling and simulation to validate the concept. This process involves time, cost, effort, and labour resources [1]. So, the designers have to wait until they get feedback from the embodiment stage. To address this issue, it is planned to understand the behaviour exploration in traditional sketch-based conceptual design. Based on this understanding, a support system is developed to facilitate the motion validation of concepts in the early stages of design. Its usability is evaluated for the designers' subjective satisfaction and mental effort.

2 Literature Review

This section broadly explores three domains which affect the sketching behaviour in the digital environment for articulated product concepts, which are discussed below.

2.1 Sketching in Design

Conceptual design is one of the important phases of design because the decisions made in this phase significantly influence the cost, performance, reliability, safety, and environmental impact of a product [4]. Hence, it is essential to provide support during this crucial phase to improve the overall productivity of the development process. Computers are extensively used in product development activities, but more support is needed for the conceptual design stage [5]. Typically, designers use sketching in the early stages of conceptual design because of its inherent advantages [6, 7]. Sketching is also helpful in the creative exploration of product concepts. Several theories have been proposed in literature [8] [9], [10] to explain the importance of the sketching process. In the early conceptual design phase, sketching is like reflective conversations with the medium and the self [11]and as a dialogue with the designer himself [8]. The designer's background (whether in arts or engineering) affects the sketching process. Such differences have been shown in [12]. [13] gives information on the affordances of design sketching, especially from the designers' point of view. [14] says that the quality of the final product is not influenced by sketching but by prior intentions within a process of pure material management. [15] discusses alternatives for sketching to enhance visual thinking.

2.2 Sketch Based Interfaces (SBIs)

Tversky [10] argued that, in design, sketching reflects the underlying conceptual structure of the domain. Thus, it is necessary to support the early stages of design. Towards this, computer-based techniques quickly visualize the shape created by the designers using sketching have been reported in the literature. For example, Teddy [16] is an application that generates 3D shapes based on sketch strokes. Another application that allows the designers to create sketch strokes in arbitrarily oriented planes is IloveSketch [17]. Similarly, other applications help visualize the shape information. It is observed that typical product concept sketches contain not only shape information but also other information related to usage and behaviour through annotations. It is essential to verify the behaviour of the concept represented for a valid product proposal. In contrast to the shape representation in sketches, which is directly observable, the behaviour needs to be simulated and verified. An example of such an application is ASSIST [18], where components are represented through line diagrams, geometric shapes are recognized from the sketches, and their dynamic behavior is simulated, relying on gestural inputs. Another tool is a sketching interface for finite element analysis (FEA) [19], which extracts details such as geometry, force interactions, and boundary conditions from sketch strokes, along with the specified material model, to simulate strength behavior. , which derives the details like geometry, force interactions, and boundary conditions with the specified material model from the sketch strokes and simulates the strength behaviour. Similarly, Mechanix [20] is a sketching application designed to solve free-body diagrams for truss problems. Additionally, a rule-based visualization of mechanical systems is presented in the literature. A rule-based visualization of working of mechanical things is shown in [21]. Here, visualization of motion of a complex mechanical system for CAD objects is generated automatically using the user constraints and inferring interaction between parts based on their geometry. Similarly, algorithms were devised to recognize kinematic mechanisms in images of hand-drawn sketches [22]. However, this requires training on textbook graphics (kinematic mechanisms) of such images. The majority of such applications use sketching as an interface. The present work aims to support behaviour exploration in an integrated sketching environment where the main activity is concept sketching, and the designer is given feedback on the behaviour (in terms of motion) without deviating much from the sketching activity. As most of the products designed have multiple parts, they also have relative motion among each other. So, sketching them as part of product design concepts is nothing but sketching linkage mechanisms if one simplifies them. Chase et al. [23]provide a review of software tools designed for the motion generation of rigid bodies.. A web-based mechanism design tool has been shown in [24]. It can compute and visualize the kinematic parameters of the individual links of mechanisms such as the four-bar, crank-slider, geared-five-bar, six-bar linkages, and cam-follower systems. For synthesising six-bar and spherical mechanisms, a modeller was associated with the design system in [25]. A recent development is by Anurag et al. [26] in motion generation as an Android and iOS application.

2.3 Usability of sketch-based mechanism design applications

Usability studies for any system are a prime requirement for its acceptability [27]. The system's acceptance is based on social and practical aspects. Practical aspects include usefulness, cost, reliability, etc. Usefulness is divided further into two categories viz: usability and utility. The utility is the question of whether the system is functioning as intended. Moreover, usability is '*how well*' is this functionality. The usability of a system is defined on specific components viz., learnability, efficiency, memorability, error, and satisfaction [27].

Usability measures have been defined and classified into effectiveness, efficiency, and satisfaction in [28]. Other definitions of usability can be seen in [29] and [30]. These definitions do not deviate much from that given in [27]. Evaluating a system using the above five dimensions is considered usability testing. Testing is done to determine whether the system has a direct impact on the users or not. Such users are intended users. Others are just users. In the rest of the work, users intended users or participants are interchangeably used. Even though the authors of the usability studies may not use the five components for their evaluation, they may define the components that match semantically.

Digital sketching interfaces have been developed considering the limitations of the traditional sketching medium. Once they have been developed, they need to be evaluated with some criteria for usability. In [31], an overview of the important sketching interfaces is presented. Some of them have used qualitative evaluation methods [32], [33], [34], and others have devised their own parameters of evaluation [35], [36], [32] [37], [38], [39] and [40]. For simplicity, at the conceptual stage of design, a skeleton mechanism needs to be sketched where the links should not cross over one another and be symmetrical [41]. The latest automatic methods are developed for sketching the mechanisms in [42] and [43]. [42] focused on planar kinematic chains with planar and non-planar topological graphs. On the other hand, [43] focused on planar kinematic chains with multiple joints.

Usability tests have been done on some of the mechanism design packages. There have been attempts to design spherical [44] and spatial mechanisms [45] in virtual reality (VR). A study on the effectiveness of traditional and VR interfaces in spherical mechanism design [46] proved that the former was chosen over the latter. Of course, the experiments performed had their limitations. M.Sketch [47] was developed to use technical non-experts for analyzing mechanisms. FoldMecha [48] is a computer-aided mechanism design system that supports the construction of mechanical papercraft. It enables users to design motion by varying component parameters. Then, the physical prototypes are built using the system-generated parts and folding nets. MechPerfboard [49] used augmented reality (AR) for designing mechanisms for path generation problems. Hand tools like wrenches, scissors, syringes, etc., have been designed by [50]. Blending artistic exploration, mechanism building, and programming is essential for interactive kinetic art (IKA). The authors made a workbench for interactive kinetic art (WIKA) [51]. [52] made an integrated approach for modelling, simulation, and optimization in the design of complex mechanical products. [53] used AR to represent machines and mechanisms in augmented reality for academic use.

2.4 Summary of Literature Review

The existing literature highlights the challenges designers face in effectively communicating the functionality of their sketches to themselves and others, as noted in Wetzel et al.[54]. Additionally, [55] have quantified these difficulties in explaining functionality. While there are various methods for conveying ideas, such as sketches and mind maps, a comprehensive examination of the challenges designers encounter in articulating functionality has not been extensively explored in the literature.

The brainwriting method was used as a means for online communication of design intent in [56]. To communicate conceptual design information, the user's different representations like FBS tree, storyboard with sketches and semantic network have been explained in [57]. Even though there are authors who developed applications, [22], [23], [25] [26], [41], [42], [44] and [45], to address the issue of behaviour exploration digitally, they used primitive geometries (lines, triangles, parallelograms, etc.) to represent the structure of the sub-components in their design. Satisfying the functional constraints is one of the primary design tasks [58]. Traditionally, it is known as a method of functional synthesis where the given set of input motion and force is transformed into the desired output motion and forces through the design process [59].

Sketches are deliberately vague, ambiguous, and not concerned with specific details [60] and [61]. A sketch's internal symbolic ambiguous structure helps the designers generate new ideas by discovering new ways of reading the same sketch [9], [62]. The literature also suggests an uncertainty or discrepancy between structurally-oriented sketching, which focuses on depicting design elements, and functionally-oriented sketching, which aims to reflect the connectivity between elements and their integrated behaviour [63]. Thus, it is important to retain the sketch's ambiguous, vague symbolic structure concerning the concept's functionality, which has yet to be utilized thoroughly. The present work aims to combine the features of sketches (especially ambiguity, which helps in generating new concepts at the conceptual stage) and the aspects of mechanism design (to represent the physics behind the concept, typically done in the embodiment stage) to simulate the motion of the articulated product sketch to help in the communication of functionality for behaviour exploration.

3 Methodology

In the conceptual stage, a support system would be useful to validate the motion requirement. The FBS model of design [64] explains the interactions among Function, Behavior, and Structure (FBS) in the design process. In this, the designer compares the expected behaviour to the actual behaviour of the product structure and iteratively modifies it to achieve the required behaviour. This comparison may become challenging. In the case of product concepts having relative motion between their components, it may be challenging to infer the behaviour of the structure. Hence, the designers must go through the interactive process of creating computer models and simulating the behaviour using sophisticated analysis tools. This process is domain-dependent, consumes more resources, and is preferred in the later design stages because most of the component's design is decided. Resources for behaviour exploration in the early design stages, especially during the sketching phase, are scarce, with no formal methodology. Consequently, concept evaluation depends solely on the designers' ability to accurately visualize component movement through *mental simulation* [65]. Overall, this shows that the designers exert effort while mentally simulating articulation. So, estimating mental effort while behaviour exploration for motion is one of the measures.

A system is needed to swiftly simulate motion based on the sketched components, offering improved insight into the motion behaviour of the sketched product while maintaining continuity in the sketching activity and associated thought process. The following steps are considered essential for conceptual sketch-based behaviour exploration

1. Understand the designers' challenges in the traditional sketching environment while conceptualizing articulated product concepts.
2. Digitally characterize the sketching annotations and gestures.
3. Identify the metrics for evaluating the digital application.

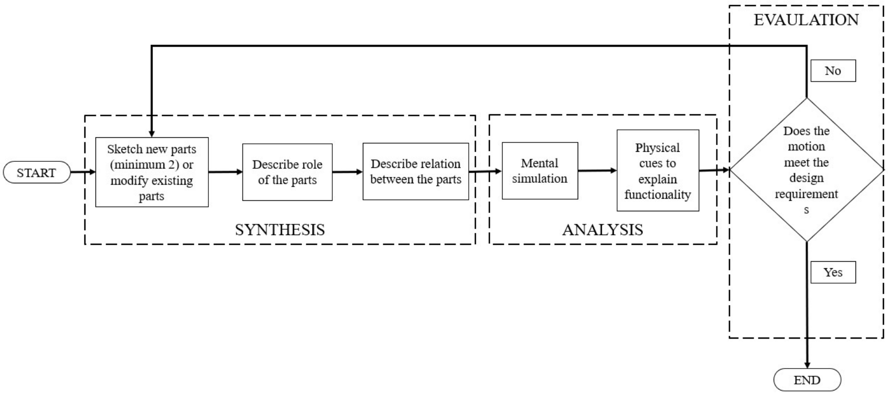


Fig. 2: Methodology followed by the designers while motion exploration

4. Estimate the effectiveness based on the metrics of whether the digital application is usable or not.

In this current work, challenges faced by the designers from the design experiment in [55] have been mentioned. With the help of these challenges, design actions have been characterized for a digital sketching environment. A software application, Sketching Interface for Mechanism Behaviour Analysis (SIMBA), has been developed, and a design experiment has been conducted to test its effectiveness and pleasantness (subjective satisfaction). For its effectiveness, the mental effort of the designers has been estimated and compared with that of the designers who used traditional sketching mediums for behaviour exploration.

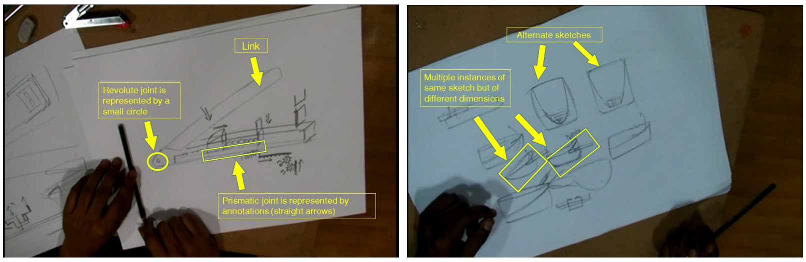
4 Sketching Interface for Mechanism Behaviour Analysis (SIMBA)

This section presents the challenges faced by designers in traditional sketching environments. These are characterized for digital sketching environment and developed as software tool. Later, usability is measured for the same.

4.1 Observations from traditional sketching activity during behaviour exploration

The difficulty of communicating the functionality of the concepts was quantified using physical actions like annotations, gestures and verbalizations [55]. Based on the same design experiment reported in [55], the following observations have been made during behaviour explorations.

1. **Incremental sketching of parts:** The ideation starts with sketching/drawing components and connecting them with appropriate connections/joints. The appropriateness depends on the designer's intended motion. Every time the designer draws multiple components (not more than three at a time), the designer connects



(a) Subject 1 (b) Subject 2

Fig. 3: Observations of traditional sketching activity during behaviour exploration (a) Subject 1 Sketch (b) Subject 2 Sketch.

them. This is the synthesis part of the methodology. Then, the designer explains the nature of motion relative to each component. Once the designer is satisfied with the motion, the designer incrementally adds more components to the existing structure. The whole sketching process for motion exploration can be modelled as shown in Fig. 2. All the mental simulations of the connected components are done in the analysis phase. The mental simulation is aided by design actions that help to know the product's behaviour. The design is complete if it matches the design requirements; otherwise, the process is repeated.

2. **Uncertainty in the design idea about functionality:** Throughout the design/sketching activity, the designer is challenged by the uncertainty of the components' motion. So, the designers go back and forth between previously drawn and current components to check whether the functionality meets the design requirements, see Fig. 2. Once, as per the designer, if the idea is generated with all their assumed performance, there is a high probability that the generated concept will not meet the design requirements. For example, if the idea is physically prototyped per the designer's intent, it might not meet the design requirement.
3. **Design actions for explaining functionality:** The designers use different design actions like verbal utterances, hand gestures, and textual annotations to explain the functionality of the sketch. In Figure 3(a), connections are represented by drawing small circles (representing revolute joints), and input and output motions are represented by arrow marks. Figure 3(a), whereas a prismatic joint, i.e., which depicts a translation motion between two parts indicated by arrow marks. Also, the subjects used unique gestures to explain the rotation and translatory motion in unique ways. For example, to explain the functionality of spring, the designers pinch their fingers using the forefinger and thumb. One hand is held in a rested position, and the other is given a two-and-fro motion to explain the behaviour of the spring.
4. **Auxiliary sketches:** The designers drew many auxiliary sketches in addition to the main sketch where the overall functionality exists. The main sketch had the main functionality, but there were certain instances where the number of components had become too large, which was difficult for the designer to handle. So, the designers used to draw auxiliary sketches on one side apart from the main sketch. This helped

them decentralize the mechanism to get clarity as the complexity decreased. It is observed that designers drew auxiliary sketches to explore and then emphasize the accepted parts by drawing darker strokes. Sometimes, the same concept needs to be redrawn with different dimensions, which occupies space on the paper, as shown in Figure. 3(b).

To tackle the aforementioned challenges, the Sketching Interface for Mechanism Behaviour Analysis (SIMBA) was created using Unity version 2021.3.7f1 on a Lenovo ThinkStation equipped with an Intel(R) Xeon(R) Gold 5118 CPU running at 2.30GHz (48 CPUs) and 64 GB of RAM. This ThinkStation also featured an NVIDIA Quadro P6000 graphics card. Sketching was facilitated through a haptic device from 3D Systems, specifically the Geomagic Touch. The software application is designed for product designs involving multiple components that move relative to one another in parallel planes, requiring that the product sketches incorporate planar mechanisms. The tool was developed using the Unity and Visual Studio game engines, with sketching performed via the Geomagic Touch haptic device.

4.2 Characterization of design actions for behaviour exploration for SIMBA

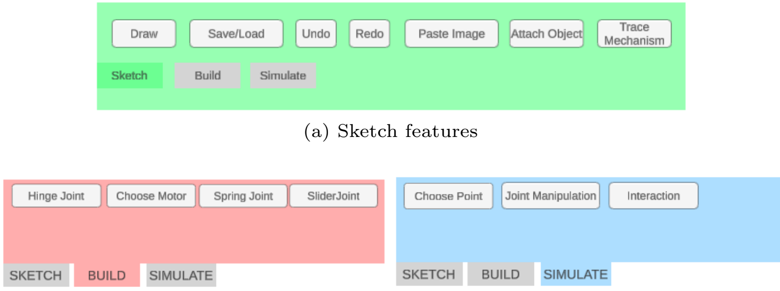
Using the observations made on the traditional sketching medium, certain features have been developed in SIMBA to incorporate its nature. Each of the SIMBA features have been categorized based on these observations as shown in Table 1.

Observations in traditional sketches	**SIMBA features**
Incremental sketching of parts	Draw/sketch, Component recognition, Connections recognition, Tracing over mechanism, Attaching objects
Uncertainity of the functionailty and testing validation of the concept	Interactive simulation, Coupler curve generation, Joint-to-joint distance manipulation
Design actions for explaining functionality	Connections recognition, simulation
Auxiliary sketches	Multiple instances sketches

Table 1: Observations in sketching activity (left column) are mapped to SIMBA features (right column)

Using the tool, the designers can sketch the articulated product concepts. The tool can recognize links and joints and simulate the mechanism. The application has three tabs, namely Sketch, Build, and Simulate. Each tab has different features to facilitate behaviour exploration of the sketch, which are explained below.

1. *Sketch*: The sketch tab (Fig. 4(a)) facilitates the creation of links and objects using the haptic stylus. Pressing the sketch button displays a message that lets the user know that sketching is enabled. Users can attach other mini sketches or images to links. The different features on the sketch tab are sketch, save, load, undo, redo, paste images, attach objects to links and trace mechanism.



(a) Sketch features

(b) Build features

(c) Simulate features

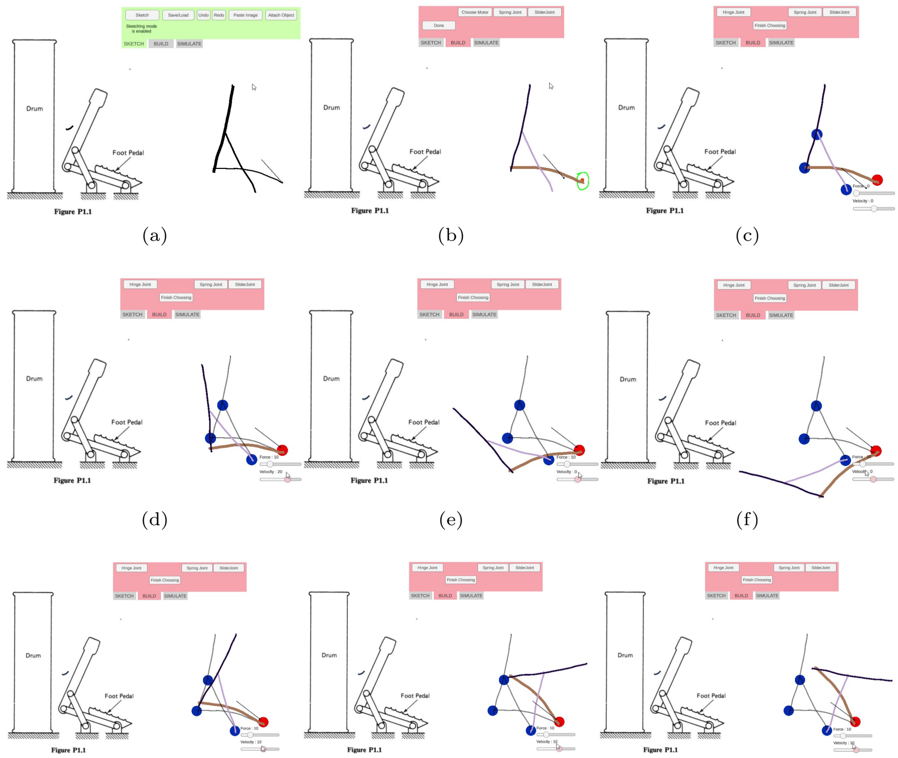
Fig. 4: SIMBA features

2. *Build*: The build tab (Fig. 4(b)) contains features that are necessary to provide motion constraints to the links that were drawn earlier. This action is performed by indicating joint constraints (rotary or slider) using sketch-based gestures.
3. *Simulate*: The simulate tab (Fig. 4(c)) contains features to simulate the mechanism and visualize the motion of different links. This also includes point trajectories, joint manipulation, and interactive simulation.

4.3 SIMBA features

The SIMBA features are individually explained in this section in the order of their workflow for simulating an articulated concept.

1. ***Recognition of Links/Components/Rigid bodies***: The form of an object depicted in a sketch is less explicit compared to a physical prototype or computer model, relying heavily on the designer's interpretation which is significantly shaped by Gestalt principles of perception and the skill involved in creating the sketch. Gestalt laws of the perceptual organization [66] help in perceiving the composition. Consider the example of the drum-beating mechanism as shown in Fig 5(a). It has four components, and the system recognises the different sub-components of the sketched concept shown in Fig.5(b). Each component is identified by a unique colour.
2. ***Connections marking and their recognition***: The type of joints defines the relationship between the motions of two links. In this work, only two motion constraints are considered viz., hinged and sliding constraints. In hinged constraints, two components are fixed at a point and can only rotate around that point. In concept sketches, designers mark hinge locations by drawing small circles at the junction of the two links. Similarly, in this interface, designers define constraints by drawing circular gesture strokes. The hinge location is determined as the average of the coordinates along the gesture stroke, as shown in Fig.5(b) and Fig.5(c). The mechanism is built using the connections and ready for simulation as shown in 5(c). The connections are shown as solid blue circles. The input for the mechanism is given at the location. Once the system recognizes the input, the blue circle turns red.



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Fig. 5: Stages in SIMBA (a) Sketching (b) Marking the rotary joints (c) Selecting an input joint (d)-(f) Input given in anti-clockwise direction (g)-(h) Input given in clockwise direction

In a sliding type of constraint, one component moves relative to the other along a predefined line of motion. This helps the designers simulate concepts with linear component motion concerning other components. This type of constraint is defined by a line along which a component translates with respect to other components. First, the designer has to select the two components between which the constraint has to be defined, and then the designer has to select the components. Then, draw a constraint line stroke to determine the sliding direction.

An intuitive way to describe motion between two links can be used to choose rotary constraints. Here, to constrain the rotary motion between two links, a circle or arc is drawn by pressing the second button of the stylus such that the circular arc intersects the two links. This helps the system to recognize the rotary joint between the two links. For a slider joint, a straight line is drawn to intersect the two links and the direction of motion is along it. Similarly, spring anchor points are chosen. The input is given to the joint, where the user will specify non-zero values for force and velocity parameters using the slider UI feature.

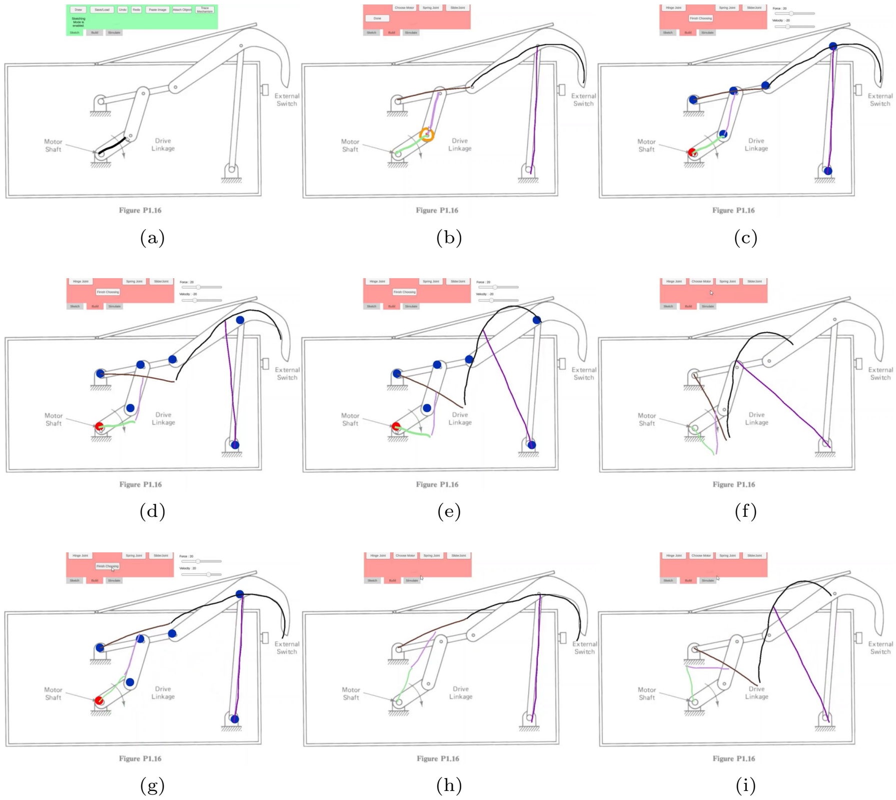
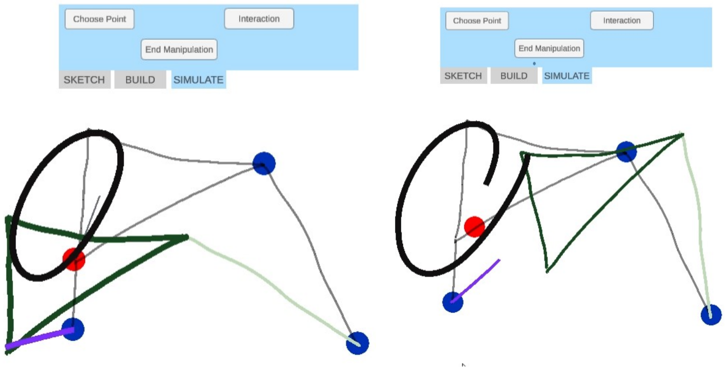


Fig. 6: While using trace mechanism feature (a) Sketching after inserting an image in the environment (b) Marking the rotary joints (c) Selecting an input joint (d)-(f) Input given in clockwise direction (g)-(h) Input given in anti-clockwise direction

3. ***Tracing over the mechanism***: Sometimes, the designers want to evaluate existing product concepts. This is facilitated by this feature, which allows the designers to trace over an image and simulate the existing mechanism. The system will identify the components and their connections to help the user explore the motion. Fig. 6 shows one of the tracings over the mechanism. This feature has been explained in detail in [67].
4. ***Interactive simulation***: In physical prototypes, motion exploration is informal; the designer manually manipulates the chosen component. In contrast, computer models offer a structured approach with predefined fixed links, input pairs, and input functions. This allows the designer to select any input pair and examine the behaviour of the connected components, closely mimicking the experience of manipulating a physical prototype. This setup makes it easier to assess any functional uncertainties.
5. ***Coupler curve generation:*** Most of the time, design requirements are represented as motion requirements. These requirements include the path traced by a



(a) Path tracing

(b) Path of the point changes after joint manipulation

Fig. 7: Coupler curve generation and joint-to-joint distance manipulation

point on a rigid body or link, the velocity of the point, dwelling during the motion, etc. All these facilities can be visualized in the current sketching environment in the concept generation, thereby helping designers to judge whether the mechanism meets the motion requirement. This is done by selecting a point of interest P on any link, and the software traces the path of the point. (see Fig. 7(a)).

6. ***Joint location manipulation***: Designers sometimes make multiple instances of the exact mechanisms with slight link length modifications that utilize space and time. Of course, older designs also need to be reviewed. To overcome the problem of wasting time and space in paper-based mode sketching, the sketching environment is facilitated with an option to manipulate the link's length. First, the joint (red in Fig. 7) is selected, which will be changed. This is done by selecting two adjacent links. This implies that the links associated with the strokes are selected. After this, the link (Figure 7 (b)) whose length will be changed is selected. Then, the joint is moved in the X and Y direction of the sketch plane to a desired location. In terms of mechanism definition, this implies a change in link lengths. The change in link dimensions can be observed in the change in shape of the coupler curve (black).
7. **Multiple instances of mechanisms**: The designers drew many auxiliary sketches besides the main sketch where the overall functionality exists. The main sketch had the main functionality, but there were certain instances where the number of components had become too large, which was difficult for the designer to handle. So, the designers used to draw auxiliary sketches on one side apart from the main sketch. This helped them decentralize the mechanism to get clarity as the complexity decreased. It is observed that designers drew auxiliary sketches to explore and then emphasize the accepted parts by drawing darker strokes. Sometimes, the same concept needs to be redrawn with different dimensions, which occupies space on the paper, as shown in Figure. 3(b).

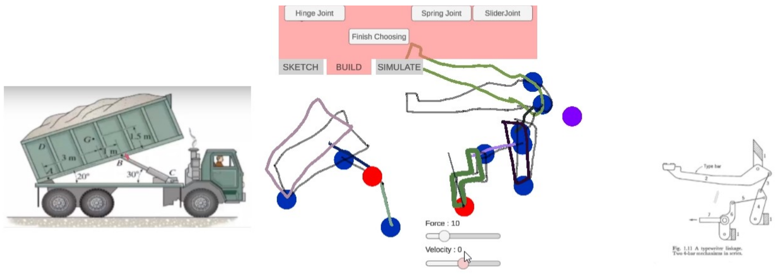


Fig. 8: Two mechanisms can be drawn in the same sketching environment, images are taken from [2]

A design experiment was conducted to evaluate the system's usability with the participants for subjective satisfaction. The parameters used to evaluate the subjective satisfaction of the application are taken from [68], which include ease of use, want-to-use, fun-to-use, and intuitiveness. Later, the data was collected, processed, and analyzed for subjective satisfaction. The hypothesis is to test the SIMBA user's subjective satisfaction with the developed features, especially for behaviour exploration.

4.4 Experimental setup

14 participants (10 males and 4 females) were involved in this experiment. The participants were studying for Bachelor's and Master's degrees in Design. The participants were in the age group of 18 to 32 years. Each participant experimented separately. The participants were given a design task to generate as many concepts as possible using the software application that satisfies a given design criteria. The problem statement was to *"design a mechanism for an underwater submarine where the desired motion was similar to that of the hands when humans swim underwater."* The desired motion was verbally described to the participants. The design requirements were clearly explained, and the participant was given time to think. Any doubts from the participants were clarified. If the participant had any doubts regarding the software usage, they were to raise their hand. Other advice, especially regarding the concept, was politely discouraged but encouraged to test their doubts on the software. The design activity was video recorded. The participants were to think aloud about their designing activity during the experiment. The maximum time for the sketching activity was 45 minutes. In addition, the participants were asked not to worry about the correctness of the outcome of the concept. If they thought the concept would work, it had to be saved. This is to make their designing activity concept-centric rather than software-based. Once the experiment was finished, the participants were asked to complete a questionnaire about software applications for data collection.

4.5 Subjective satisfaction of SIMBA

The collected data has to be analyzed to ensure the designers' subjective satisfaction. The test/questionnaire is also verified for reliability using Cronbach's alpha.

4.5.1 Data collection

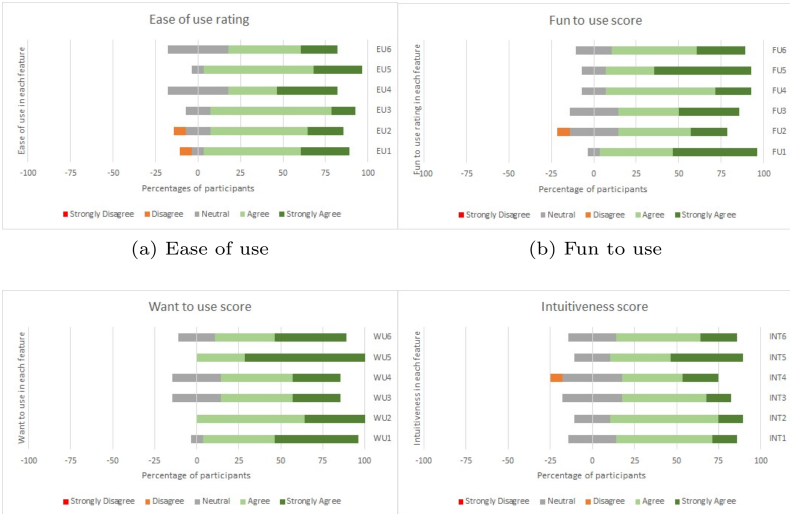
The questionnaire asks the participants to rate the features of the software application using parameters. Each question referred to a specific feature evaluated using the parameters. The following features were evaluated of the software are sketching(F1), building (F2), attaching objects and images (F3), motion visualization (F4), path tracing F5), and joint manipulation (F6). The four aspects of subjective satisfaction are easy to use (EU), fun to use (FU), want to use (desires) (WU), and intuitiveness (INT). So, WU3 refers to the measure of the want-to-use parameters for attaching objects and images.

For each data point, the participant has their choice, viz., a five-point Likert scale of 1-5 was used where 1 respresents Strongly Disagree (SD) and 5 represents Strongly Agree (SA). Each question was asked about a specific feature of the software. After completing the questionnaire, the participants were interviewed about their overall experience and shortcomings of the software application. The answers were audio recorded. The questionnaire was filled out by the participants using a Google form. The questionnaire was set per Likert's scale [69]. The authors have taken approval from the ethics committee for the experimentation and data collection method. There were no duplicates in the questionnaire. Every feature was evaluated against the four factors, and the results have been plotted in Fig. 9.

4.5.2 Data analysis and Results

The reliability of internal consistency among the questionnaire items was assessed by calculating Cronbach's alpha [70] using the IBM SPSS software [71]. The resulting Cronbach's alpha for the current questionnaire was 0.871, well within the acceptable range of 0.7 to 0.95 [72]. The primary aim of the study was to evaluate participants' subjective satisfaction regarding each feature based on specific parameters, rather than comparing satisfaction across different features

From Fig. 9, it can be seen that the participant's overall satisfactory experience with SIMBA. There is a slight disagreement in ease-of-use and fun-to-use, i.e., 7% of participants expressed dissatisfaction with the sketching feature. For all the remaining features, all the participants showed more than neutral satisfaction. That means the participants did not show negative subjective feelings or displeasure while using the application. The other EU parameters had a minimum score of 3 (Neutral), which shows that the participants had a neutral feeling for EU2, EU4, and EU6. EU3 and EU5 had a minimum score of 4 (Agree). For the parameter that is wanted to be used, the minimum score was 3 (neutral feeling) for all the features. This shows that the participants had a desire for all the features. The fun-to-use parameter's minimum score was 2 (disagree) for FU2. For others, the participants "Agreed" at least that the SIMBA had a fun factor involved in it. The intuitiveness parameter's minimum score was 2 (disagree) for the INT4 feature. For all others, the minimum score was 3. This



(a) Ease of use

(b) Fun to use

(c) Want to use

(d) Intuitiveness

Fig. 9: Subjective satisfaction of the participants

implies that the participants had at least a "Neutral" feeling about the intuitiveness of the SIMBA. They did not have a negative feeling, which indicates that SIMBA features were intuitive enough to learn and use. All the features created a positive satisfaction except F2 (building mechanism) and F4 (motion visualization).

Participant P2 reported difficulty in getting used to the stylus of the haptic device. Participant P5 reported that the smoothening of the strokes could be a nice aesthetic visual to the sketches. Participant P5 reported incorporating a new feature to smoothen the strokes that were drawn. But as per literature [11], once the naturality of the strokes is manipulated, it will affect the cognition of the designer. Hence, this feature could be optional in the future.

There was no option for removing the joints at a later stage. Once the designers sketched the articulated product, they had to add the joint constraints. If there was a mistake in adding a joint constraint at a location, there was no option to remove it and add it again. The author's main intention was that once the sketching was done, the idea was to be frozen. Then, the sketch is ready to be given motion constraints and later simulated.

Before the experimentation, the participants were given some initial demonstration of the software. Then, they were asked to use the software by simulating some examples (from [2]). On average, with some suggestions, the participants easily understood the working flow of the SIMBA. This shows that given an articulated product design, it was easy for the participants to draw and analyze the mechanism in no time.

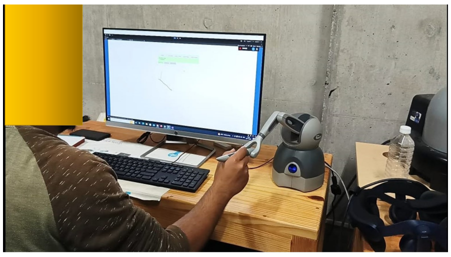


Fig. 10: Experimental setup

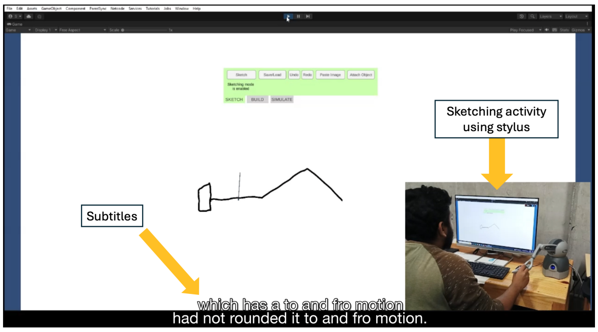


Fig. 11: Processed PIP video ready for coding

5 Estimation of mental effort

As mentioned in section 4, the participants of the design experiment generated design concepts by using SIMBA. A think-aloud methodology is used in which the designer will verbalize his thought process to externalize the intended behavior through the design actions. This design activity is audio and video recorded which is anylyzed using protocol analysis. A modified coding scheme based on [73] is follwed for the analysis.

5.1 Data processing

The raw data in the form of audio-video has been transcribed and refined. The authors used Adobe Premier Pro to transcribe and refine the verbalizations. The final audio video was processed in the form shown in Fig. 11. The processed videos with subtitles have been given to three coders. The coding scheme used to process the data was the same as mentioned in [55]. The coders were not given the final outcome to keep the results unbiased. The inter-coder reliability of the data is shown in Table 2. The inter-reliability was in the range of [0.68, 0.97], which is above the acceptable standards, i.e. 70% [74]. These have been mentioned in table 2. The processed data from the coders has been used to estimate mental effort for four participants (3 male and one female).

To understand the behaviour exploration it is necessary to distengwish the design actions (sketching) pertaining to the explanation of the functionality of the sketch.

Through this categorization, the mental effort involved in behaviour exploration was estimated.

5.2 Data analysis and Results

S.No.	Particip-ants	Video duration (seconds)	Mental effort %	Kripendorff alpha
1	P8	488	8.45	0.68
2	P7	855	20.9	0.92
3	P5	1308	5.26	0.78
4	P2	1006	20	0.97

Table 2: Inter-coder reliability results

Parameter	Traditional	SIMBA
Minimum	51.4	5.26
Maximum	69.33	20.9
Mean	58.89	13.64
Median	57.405	14.2
Q1	54.51	7.62
Q2	57.405	14.2
Q3	61.78	20.23
IQR	7.27	12.61

Table 3: Comparison of mental effort between traditional sketching medium and SIMBA

The results show that the mental effort to explain the functionality ranges from 5.26 to 20.9%. Compared to the results obtained in [55], the mental effort to explain the functionality greatly decreases when the SIMBA has been used. The average mental effort in [55] was above 58.89%. The average mental effort estimated in this study is 13.625%. There is a decrease of 77% in mental effort. This shows that the digital sketching environment's characterisation has effectively decreased the mental effort to explain the functionality. Even though the sample size is small for the current study, the results here have been consistent, which is below 25%. A clear difference can be seen in Fig. 12. The mean, median and quartile information can be seen in the table 3. The maximum mental effort estimated for SIMBA does not fall in the IQR of the traditional one. The study can be further statistically validated by automating the recognition of the design actions in the sketching activity.

The sketching activity of the participants was studied to determine their challenges that can be divided into the categories as per Fig. 2 at different stages, viz., synthesis, analysis, and validation. During synthesis, the participants could draw the elements and establish a relation between them in the articulated product concept seamlessly. Most of the participants used a match-stick figure as their inspiration to generate

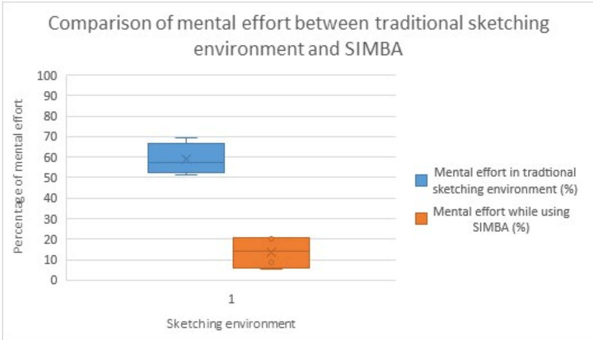


Fig. 12: Box plots mental effort between traditional sketching medium and SIMBA

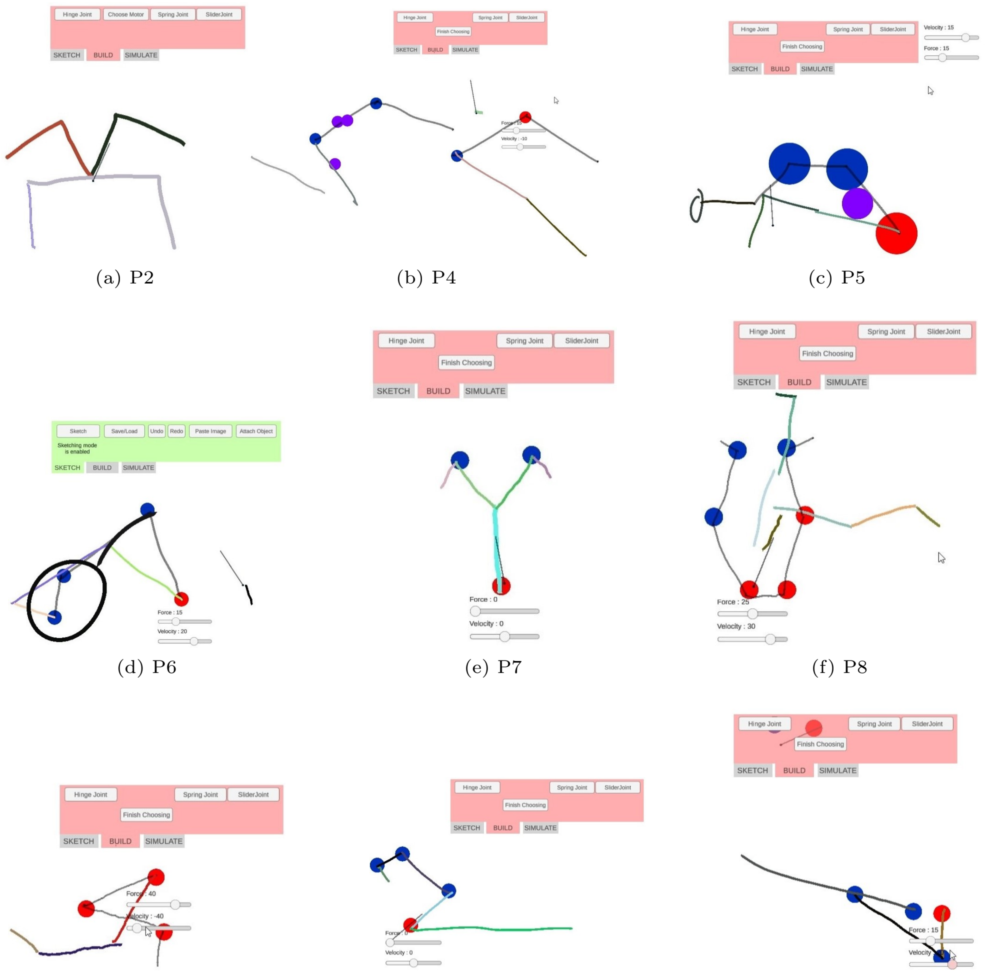
a concept (see Fig. 13(a) and (e)). In reality, the neck and shoulder are not joined together at a point. Technically, the abstraction itself was not up to the mark. This led to establishing wrong or inappropriate motion constraints to the sub-components.

During analysis phase of design, a motor is a device that converts electrical energy to mechanical energy (continuous motion rotation or translation). Participants faced a technical challenge here. They failed to notice the fundamental function of the motor, and they were expecting the software application (SIMBA) to give their own required characteristic motion. Some participants asked for rocking (or to and fro motion) of a particular sub-component. This rocking motion can be analyzed using a 4-bar mechanism. The appropriate dimensions for a given range of motion can be obtained from the methods mentioned in [75]. Perhaps the lack of this technical knowledge is somewhat blamed on the software that has to provide such an option. Range of motion for a particular component was also demanded.

During evaluation phase, the articulated product concepts generated by the participants do not meet the criteria mentioned in the design requirements except for participant P4. This articulated product differed from the rest because he used a 4-bar mechanism to get a rocking motion. The solution made by P4 seems most reasonable. To evaluate, the current concepts have been modelled in ADAMS software as shown in Fig.14. The abstract skeleton structure is converted into a digital model in ADAMS. As such, the design outcomes do not work if implemented "as they are", and an extra effort is to be made to make them work.

6 Discussion

On careful observation, the participants' approach to designing articulated product concepts in SIMBA did not change compared to the traditional sketching medium. The designers largely followed the synthesis, analysis and evaluation (mentioned in section 3.1) loop. There was not much deviation from this process. The participants used the SIMBA to check whether the product concept's motion behaviour could be explored. This is also called behaviour exploration for motion. Earlier, in static sketches, this knowledge was unavailable to the designers, which made their concept generation difficult, as mentioned in [54]. Fig. 5 (bass drum mechanism sketch) shows



(a) P2 (b) P4 (c) P5

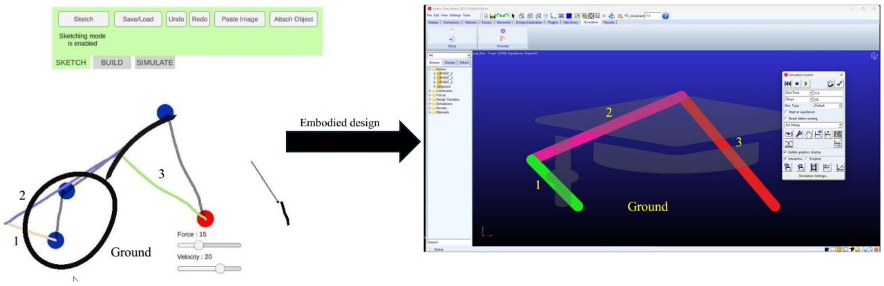
(d) P6 (e) P7 (f) P8

(g) P9 (h) P11 (i) P12

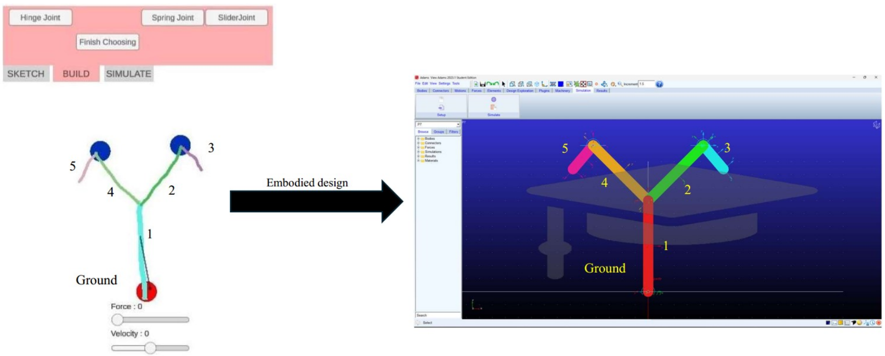
Fig. 13: Some of the design outcomes from the experiment

snapshots captured at discrete time intervals to illustrate the simulation of the two product concepts being explored. Moving components are highlighted in blue, while static components are shown in black shown Fig. 5(a). The designer can explore how much the crank has to rotate to move the drumstick as close as it is to the drum. Fig 5(d)-(i) shows the relationship between the drumstick and foot pedal rotations (in both clockwise and counterclockwise directions) across various phases. Such inferences are challenging to obtain from static sketches.

The concept of structurally- and functionally-oriented sketches have been combined in the current work, which was observed as a gap in [63]. The "naturalness" of the traditional sketching activity was characterized and integrated in SIMBA to simulate



(a) Embodiment of P6 concept



(b) Embodiment of P7 concept

Fig. 14: Embodiment of the SIMBA models in ADAMS

the articulated product concept sketches. The naturalness and the additional advantage of decreased mental effort have been effective. The main reason for the decrease in mental effort can be attributed to the "technology intervention" of the software application. All the effort required to visualize the motion mentally (in a traditional sketching medium) has been offloaded to the physics engine of the software application.

Designers can also refine the motion to meet the requirements by adjusting the joint location. In the SIMBA design experiment, the feature was used to try out variations of the concept the designers generated. Even though the sketching application has achieved its goal of motion visualization of a product concept without deviating from the traditional sketching activity, its response concerning each factor of subjective satisfaction was positive. This shows that there is a level of satisfaction among the participants while using the sketching application to visualize the motion of the product concept. This shows that even though the primitive geometries have not been used to represent the links or rigid bodies as it was mentioned in [22], [23], [24], [25], [26], [41], [42], [44] and [45] the designers were able to visualize the motion without any discomfort or difficulty. This may be because the concept ideas came from their minds, and it was easy for them to relate to the product concept in the sketching application. The difficulty or discomfort may increase if they are asked to read or re-interpret the designs made by others. In this aspect, the criteria for the re-interpretation of one designer should match the intention of the idea of the original owner of the sketch. Thorough usability (effectiveness and efficiency) testing in the future may reveal further feature improvements. Some features, such as path tracing, joint manipulation and multiple mechanisms, have been reported as "beneficial" features for sketching articulated product concepts by participants.

7 Conclusion

From this work, it can be concluded that the sketch-based interface for the ideation of articulated product concepts greatly reduces the mental effort of the designers (77% reduction in mental effort) compared to a traditional sketching environment. Two types of evaluations were performed i.e. subjective satisfaction of the interface by the designers, and the estimation of mental effort of the designers. An interactive software tool, SIMBA, enables the synthesis, analysis and evaluation of articulated product concepts. The application incorporated the aspects of the sketching activity into a digital sketching medium so that the users do not digress away from the sketching activity and simulate their concepts for motion validation.

Subjective satisfaction with the SIMBA was measured with respect to four parameters: ease-of-use, want-to-use, fun-to-use and intuitiveness. The overall results say that the software was 'liked' by the designers for its features that involved sketching, building mechanisms, and simulating them. This application can also be used to visualize the motion of articulated planar concepts. This type of system also greatly enhances designers' learning of behaviour exploration in articulated product concept sketches.

Supplementary information. The following supplementary materials are provided along with this article.

- SIMBA software. (Folder name: SIMBA.zip)
- Video recording of the sketching activities of four participants. (Folder name: Processed videos for transcription)
- Spreadsheets that contain the protocol analysis of the four participants. (Coding_IJDeM.zip)
- Screen recording of the simulations mentioned in the paper. These are for Fig. 6, Fig. 6 and Fig. 8. (Videos related to the article)

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