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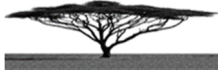
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# A functional vision based human simulation framework for complex social system design

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*Digital Human Modelling (DHM) is rapidly emerging as one of the most cost-effective tool for generation computer based human-in-the-loop simulations for a better understanding of human behaviour under complex systems. In this paper we present a functional vision based human simulation framework (visDHM). It incorporates human visual acuity based central, mid and peripheral FoV assessment of objects in both qualitative and quantitative manner. It relies on a variable resolution cube-grid acting as retinal receptor surface for processing of visible visual information that can be visualized qualitatively. For quantitative estimation, this framework takes into account some important visual parameters like acuity, accommodation and saliency. Based on these parameters, the visual information is analysed and an index to signify object clarity (legibility-index). This index varies between 0.0 (low) to 1.0 (high) representing clarity (legibility) of an object in workspace with respect to an operator. A prototype implementation has been illustrated using an optotype and a workspace object. The visualization and simulations results indicate that the index consistently matches the visual quality of the object that can be used for vision based simulations. This framework can be used for modelling objects usable for human vision requirements, identifying target population for using a product and simulating visual behaviour of humans for any given product. The present framework is limited to functional visual characteristics like field of vision, acuity and accommodation. Spatial factors like object illumination, recognition and location are not modelled and kept for future work.*

*Keywords: Vision simulations, Human-in-loop simulations, Digital Human Models, Object legibility, Complex Social Systems*

## 1 Introduction

Humans constantly interact in complex social systems hence maintaining sustainability and cost effectiveness of human interactivity is necessary by any organization responsible for its design, development and maintenance. Designers have long been relying on interactive simulations that are well suited for analysing large and semi structured problems. Digital Human Modelling (DHM) is rapidly emerging as one of the most cost-effective tool for generation computer based human-in-the-loop simulations for a better understanding of human behaviour under complex situations. For any kind of interaction, human vision is the primary channel for processing perceptual information. It is important to include its functional capability in the design process which otherwise is not readily available to the designer. Functional vision is an individual's ability to apprehend the visual information in a variety of tasks on the basis of its eyesight (acuity), near and far vision (accommodation), visual fields and eye movements. The quantitative support to evaluate feasibility of vision dominant tasks and the surrounding workspace design is gradually evolving and is our present goal of research.

In this work we are trying to answer following two questions:

- i. For a given human vision capabilities like acuity and accommodation, how to design a product for its ease of use?
- ii. For a given population with fixed vision capabilities using a product that is already designed, how to simulate human visual behaviour and quantify its ease of use?

To answer these above-mentioned questions, we present a functional vision based human simulation framework that incorporates human visual acuity based central, mid and peripheral field of vision (FoV) assessment of objects in both qualitative and quantitative manner. It relies on a variable resolution cube-

grid acting as retinal receptor surface for processing of visible visual information that can be visualized qualitatively. For quantitative estimation, this framework takes into account some important visual parameters like acuity, accommodation and saliency. Based on these parameters, the visual information is analysed and an index to signify object clarity (legibility-index). The index varies between 0.0 (low) to 1.0 (high) representing legibility of an object in workspace with respect to an operator. A prototype implementation has been illustrated using an optotypes and a workspace object. The visualization and simulations results indicate that the index consistently matches the visual quality of the object that can be used for vision based simulations. This framework can be used for modelling objects usable for human vision requirements, identifying target population for using a product and simulating visual behaviour of humans for any given product.

This paper is organized in the following format. In section 2 as background to the framework we first look at the human-centered approach for designing a sustainable complex system, human vision and its impact on sustainability of social system and then the use of digital human modelling for visual ergonomics design and simulations. In section 3 we discuss an overview of proposed framework and in section 4 we discuss the concept of FoV dependent acuity in humans that serve as a motivation for our work. We further describe the model and data-structure of a variable resolution cube-grid acting as receptor surface for sampling of spatial information in DHM vision model. In section 5 legibility assessment methodology is described that takes into account several human and object dependent visual parameters. In section 6, we present simulations and results using an optotypes and a workspace object based on functional implementation of discussed framework. In section 7 we discuss the usage and scope of this framework. Conclusions to the presented work are presented in section 8.

## **2 Background**

### **2.1 Human Centered approach for sustainability of Complex System**

A complex system comprises of a set of elements that are orderly and interrelated to make a functional whole. Those complex systems that rely on human interactions and directly or indirectly affect humans are considered as complex social systems [49]. Hence maintaining sustainability and cost effectiveness is necessary for self-sustainment of the organization under which such systems are maintained. Designing a complex system involves planning, knowledge and understanding of human behaviour in order to respond and adapt to the uncertainties that may arise while dealing with humans and the materials. In order to maximize human performance the elements of purpose, people, structure, techniques and information must be coordinated and integrated appropriately [35, 28]. A key design issue is that the information about range of human capabilities is mostly not available directly to the designer [43]. It is essential because of large variation of human characteristics across population, gender and age. Traditional methods for testing involves qualitative approaches like experimental strategies, ethnographic design, behavioural observation and open ended interviews [13], the results of which are converted quantitatively to match the requirements of designer. However, generally these studies are regionally confined and it is not feasible every time to assess the interaction of a large human population with system for testing each and every aspect of design. As a result, a well-designed product by the designer may fail to cater basic human interaction requirements for certain population. However with some modifications, some of the products can be redesigned and put back into service if human performance can be estimated.

## **2.2 Human Vision and its impact on sustainability for the development of a Social System**

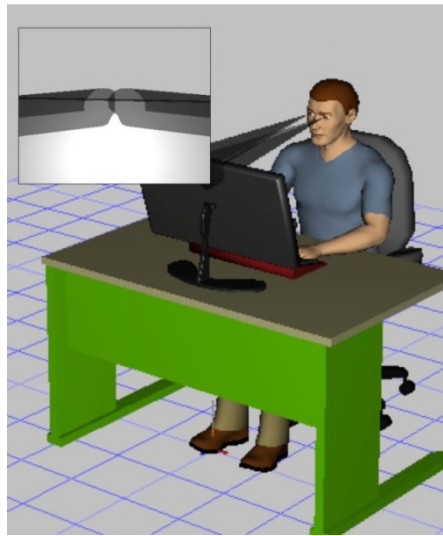
Human behaviour and performance in any given system is based on biomechanical, physiological, and psychological capabilities of the human [1]. For any kind of interaction human vision, is the primary channel for processing perceptual information. Under human visual system capabilities, biomechanical includes head and eye anthropometry that act as the primary sources for sensory spatial information; physiological includes the eyes and brain with their combined ability to collect visible spatial information; and psychological, involves processing, interpretation and response generation based on the knowledge and experience of human. Different phases in human performance include spatial searching, object recognition and localization, reaching to grasp, manipulation of objects, evaluation of the task progress, and completion [19, 30]. The ways vision enables these activities are quite distinct. For instance peripheral vision is used in searching while central vision helps in recognition. While interacting with workspace objects, visual information is either received directly while interacting with tools and reading text, or indirectly by seeing things through monitors and microscopes. Several factors determine visual capabilities of the operator and the effectiveness of corresponding tasks. Vision is the main vehicle enabling identification of objects, orientation in space, and adaptation to changes that occur in familiar environments. Functional vision for humans is their ability to apprehend the visual information in a variety of tasks utilizing the visual attributes like near and distance vision, visual fields and eye movements [10].

With the rise in human population, it has become important to consider visual system characteristics as the primary necessity to a sustainable vision friendly system. In the current world, a significant number of people are affected by low vision and several visual impairments like myopia, hypermetropia, cataract and complete blindness. Human vision or eyesight is often measured in terms of acuity to quantify the clarity of visual quality. Acuity of 20/20 is considered as normal vision. Low vision is acuity less than 20/60 (20/40 for United States) while a vision less than 20/400 (20/200 for United States) signifies complete blindness [23]. Population statistics of year 2011 produced by WHO states that out of 6000 million people across the world, around 135 million people had partial sight and over 285 million people in the world were visually impaired, of whom 39 million were blind and 246 million had moderate to severe visual impairment [32, 33]. Among the world population affected by blindness 7% are in between ages 15-44, 32% are in between ages 45-59, 58% are in between age 60 and above. With the growth of world population it is predicted that without extra interventions, these numbers are expected to double by year 2020 [16, 14]. The challenge today is to develop frameworks aimed towards design of vision friendly products and services that serve the marketplace today, while ensuring the product or its production does not negatively impact future generations. Vision is one of the fundamental attributes a person needs to access and use everyday products. Failure to take account of this reduced functional capability in the design process results in users becoming excluded from product use but also from jobs that demand high visual inputs. The quantitative support to evaluate design feasibility of vision dominant products, tasks and workspaces is gradually evolving and is our present goal of research.

## **2.3 Digital Human Modelling for Visual Ergonomics Design and Simulations**

In recent times, moving away from traditional design process and using Digital Human Models (DHM) for virtual simulations of human interaction with the product has helped the designers significantly. DHM technology offers human factors and ergonomics specialists the promise of an efficient means to simulate a large variety of ergonomics issues early in the design of products and manufacturing workstations. With this advanced technology, human factors issues are assessed in virtual digital prototype of workstation with digital human model. Most products and manufacturing work settings are specified and designed by

using sophisticated computer-aided design (CAD) systems. By integrating a computer-rendered avatar (or humanoid) and the CAD-rendered graphics of a prospective workspace, one can simulate issues regarding who can fit, reach, see and manipulate [8, 9]. The implementation of digital human model reduces and sometimes eliminates the requirement of dummy model, cardboard manikin, 2D drawings and even real human trial in expensive physical mock-ups. This technology has reduced the design time, cycle time and cost of designing new products along with improvements in quality, production, operation and maintenance costs. Being a relatively new area of research and development current DHM applications are mostly dominant towards whole body posture and biomechanical analysis used for simulations of material handling tasks mostly dominated in the areas of automotive production, assembly line simulations and vehicle safety [2, 11]. For grasping and reach simulations hand model specific approaches have been developed [45].



*Figure 1 screen-capture of Siemens Technomatix JACK software*

For modelling and simulation of vision dependent tasks, the present DHM tools are mostly limited to qualitative visualization techniques like symmetric FoV cones and line of sight based visibility analysis. For instance, in [8] Siemens Tecnomatix JACK has been used to evaluate vehicle dashboard visibility and driver's visual field using the uniform Field of Vision (FoV) cones. In [36] similar FoV cones are used to assess direct exterior vision of a postal delivery vehicle driver. Similar uniform FoV based vision analysis tools are available in other DHMs like Delmia Human, Humancad/SAMMIE and RAMSIS. For simulation of traditional assembly tasks active and continuous visual feedback is required during alignment and fastening phases. Fig. 1 shows a simulation performed on student's version of Siemens Tecnomatix JACK software [4] showing a human in sitting posture, with arms resting on table, looking at top of a computer monitor. The visibility cones coming out from eyes can be seen in dark grey colour. A part of monitor visible in vision cones is shown in top left box. Vision plays a key role in precision assembly tasks and requires a close integration of visual and manual feedback. For simulation of such tasks, the present state of art in DHM technology provides valuable but very limited information. It is not possible to design and simulate tasks and evaluates the human performance that is highly dependent on



operator's visual capabilities. We believe that since the support for comparative assessment of any system with respect to human vision is very narrow in DHM although it is very important, the industry uptake is very limited. Vision modelling for DHM involves incorporation of visibility analysis using binocular FoV with vergence, legibility analysis using realistic eye modelling with retinal anatomy and pupil behaviour for modelling acuity, accommodation, dark adaptation, hand-eye coordination for visual guidance of reach and tracking tasks, cognitive modelling for object recognition and understanding. Thus, the possibilities of providing sensory assistance to DHM opens up new opportunities towards simulation of natural performance for automatic identification of issues in a given work scenario [7].

### 3 Overview of Vision Framework

The proposed vision framework (visDHM) for DHM is build over the standards of human vision with the central idea of providing both qualitative and quantitative simulation capabilities to the designer. visDHM is an enhancement to our geometric vision modelling framework described in [38]. It partially shares its data space and methods with newly developed legibility framework to quantify clarity of any given object. The model previously developed provided qualitative estimation of visible workspace on the basis of realistic FoV. visDHM was developed over it to enable more advanced qualitative as well as quantitative estimations. To enable this, we developed legibility framework that is discussed in detail in this paper. The new framework enhances visDHM by providing a human visual acuity based central, mid and peripheral vision assessment. We went in depth to develop a new variable resolution cube grid acting as retinal receptor surface for sampling of visible visual information reported by visibility framework. This framework takes into account several human and object dependent visual parameters that can be personalized across population and objects. Using this framework visDHM shows a rendering of object over retinal surface. It also reports a numerical value between 0.0 (low) to 1.0 (high) representing legibility of an object for a given human and workspace configuration. Block diagram shown in Fig. 2 show the two separate modules consisting of visibility analysis framework (Fig. 2a) and legibility-assessment framework (Fig. 2b) that is discussed further.

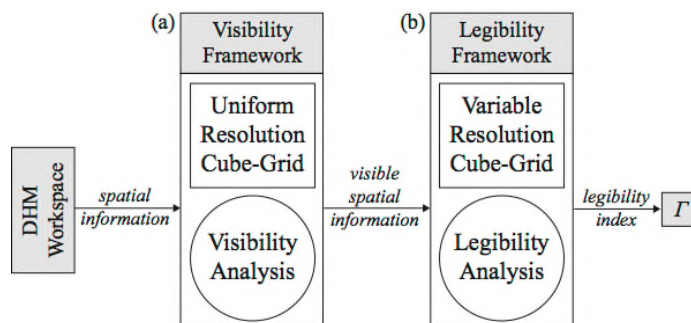


Figure 2 visDHM Architecture showing two modules: (a) Visibility analysis framework comprising of uniform resolution cube-grid and computational model for visibility analysis and (b) Legibility assessment framework comprising of variable resolution cube-grid and computational model for legibility assessment

In 2012, Sen. et. al. [38] vision introduced a DHM vision modelling framework for performing gaze-dependent FoV based workspace visibility analysis. Based on a 3D scanned human head, this model computes realistic gaze-dependent FoV with respect to location of pupil and the facial features (Fig. 3a). Similar to human visual system, virtual objects present in the workspace are marked as visible if they are

contained in the asymmetric FoV cone. The computational framework behind this model relies on a uniform cube-grid having 6 faces. It integrates a unit-cube representation of a  $360^\circ$  direction with each face covering  $90^\circ$ . The FoV cone is represented on the unit cube by projecting the pre-image of the FoV on the unit cube (Fig. 3b). The visibility of a given object can be determined with respect to the FoV by projecting the object on the unit cube and classifying it with respect to the projection of FoV (Fig.3c). Objects located in virtual space are taken as triangulated CAD models that are projected on this cube-grid. Visibility filtering is based on containment of point and triangle with respect to FoV. As a result, the framework reports the object (or part of object) visible in workspace and throws it as output (Fig. 2a). In this framework a grid-size of 30 is considered optimal for computations, with each grid cell covering a visual information located in  $3^\circ$  of 3D workspace. In that work, the visual performance analysis was limited to qualitative assessment object/workspace visibility.

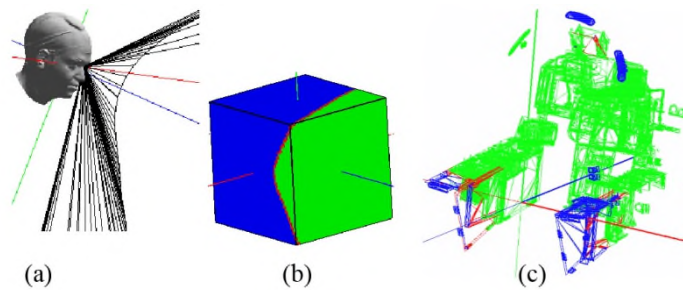


Figure 3 Visibility Analysis Model [38]

The legibility-assessment framework is the next step to enhance our DHM vision model. The central idea lies in making sense of visible spatial information that can help in more advanced behavioural simulations. For legibility assessment, the output of visibility-framework, i.e. the visible spatial information is taken as input of legibility-framework as shown in Fig. 2. The information is passed onto a newly developed variable resolution cube-grid. It provides a capability to sample visible spatial information at variable resolutions across different FoV regions. This functionality helps in simulating human acuity dependent FoV in DHM and also in visualization. Section 4 discusses model of variable resolution cube-grid. For the quantification, the spatial information is processed using a computational model that is discussed in section 5. The analysis is based on actual human visual parameters for simulation of eyesight, near and far vision that can be personalized across population and workspace objects. The designer gives it as an input to visDHM. The assessment is based on workspace configuration comprising of operator's head in a given posture with respect to location of an object. As a result, this framework reports a numerical value (legibility index) between 0.0 (low) to 1.0 (high) that represents legibility of the given object with respect to DHM.

## 4 Human Acuity based sampling of visible spatial Information

### 4.1 Variation of Human Acuity with FoV eccentricity

At a fixed gaze angle and focal distance visual acuity for humans is defined as the angular separation between two just perceivable points [41]. It is directly correlated with the resolution of receptor cells located on the retinal surface. Due to variation in size and distribution of photoreceptor cells on retinal surface, acuity varies eccentrically with FoV. It is highest at fovea (centre of retina) and gradually

decreases towards periphery with increase in size of receptor cells. Due to this the central region is capable of gathering clear and sharp visual information whereas the peripheral region is responsible for blurred vision. Fig. 4 shows an illustration a scene as it is projected onto the retina [18]. For the standard human population, central FoV with visual angle of  $1^\circ$  at the centre of retina has the largest number of retinal receptor cells leading to a highest acuity of 1.0. Due to very high density of cells in this region, spatial information can be sampled by the frequency of 1/60th of a visual degree. The high-resolution information sampling in this region leads to a perception of sharp, detailed and legible object. This is responsible for precision vision in humans. Snellen tests often use 1/60th of a visual degree as the measure of standard acuity for eye examinations using a set of legible optotypes. Acuity in the middle FoV region with visual angle varying between  $2^\circ$  and  $20^\circ$  ranges from 0.7 to 0.1. Acuity in peripheral FoV ranging from  $20^\circ$  and beyond remains fixed to 0.1. Because of very low acuity in this region objects do not appear very sharp and clear. For dealing with this drop-off in acuity, the eye (and head) in humans is equipped with muscles that allow them to align objects of regard such that the projected images always land on the fovea. Hence central (foveal) vision plays an important role in deciding legibility of spatial objects.



Figure 4 Image on the retina from [18] showing the sharp image at center and blurred image at periphery

In [48] figure labelled as “Daylight Visual Acuity For Different Parts of the Eye” has shown the variation of human acuity (for standard population) with respect to FoV eccentricity for a single fixation point. However, in normal cases eyes voluntarily fixate up to  $2^\circ$  for gathering spatial details of the perceived object [40]. The resulting acuity ranges after compensating for these small fixations makes the central FoV region slightly wider up to  $2^\circ$  with acuity of 1.0. Acuity in middle FoV region averages to 0.3. The peripheral acuity almost remains unchanged at 0.1. The modified acuity distribution is shown by the dashed-line in Fig. 5. Red, green and blue bars in Fig. 5 represent average acuity in central, medium and peripheral FoV regions respectively.

#### 4.2 Variable resolution Cube-Grid

Objects located in DHM workspace are geometrically projected on the cube-grid that acts as the receptor surface. For legibility analysis, the resolution of the receptor surface plays an important role as the sampling array imposes a final limit on the visual capabilities of the human eye. In this framework, the uniform

resolution cube-grid from [38] is modified to a variable resolution cube-grid. The resolution taken is similar to human acuity resolution, such that information projected on the cube-grid can be sampled similar to human retinal sampling. To simplify the model, the FoV is quantified into three regions viz. central, medium, and peripheral. As a standard for each region, an average human acuity of 1.0, 0.3 and 0.1 is taken respectively (Fig. 5). But it can be modified with respect to different subjects.

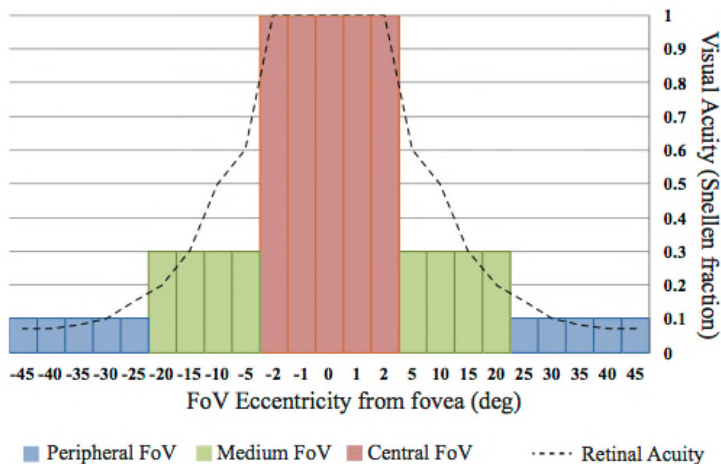


Figure 5 Visual Acuity vs FoV Eccentricity from fovea including minor fixations

In order to discretely sample the projected visual information with a desired rate, double the required sampling rate is implemented according to Nyquist frequency theorem [31]. Since the resolution of receptor cells is very high in central FoV region, corresponding grid-cells in the cube-grid should be fine as compared to grid cells located in medium and peripheral FoV. The required sampling rate for each FoV region along with its respective resolution is given in Table 1.

Table 1 Grid-Cell distribution for variable resolution Cube-Grid based on human acuity

FoV Region	Central	Medium	Peripheral
Area covered	$\pm 2^\circ$	$\pm 2^\circ$ to $\pm 20^\circ$	$\geq \pm 20^\circ$
Acuity	1.0	0.3	0.1
Sampling rate	1/60	1/18	1/6
Grid resolution (cells per $^\circ$ )	120 cells	36 cells	12 cells

Based on this fact, data-structure of the uniform cube-grid in [38] is modified to a variable resolution cube-grid. We present it in next section. Fig. 6 shows an illustrative representation of uniform versus variable resolution cube-grid.

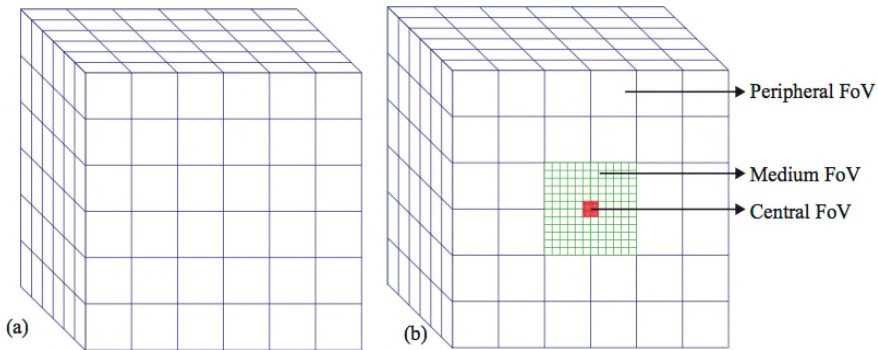


Figure 6 (a)Uniform resolution Cube-Grid in [38] (b) Variable resolution Cube-Grid

### 4.3 Data structure of Cube-Grid

Cube-grid is structured space resulting from the connectedness of six uniform 2D face-grids to cover complete 360° direction unit-sphere. These face-grids are referred to as “primary face-grid(s)” and are used for projecting visual information located in 90° FoV along all six cube directions viz. front, back, top, bottom, left and right. Each primary face-grid consists of overlaid  $n_g^2$  grid-cells that act as primary receptor surface in our legibility-framework (Fig. 8). We call these grid-cells as “primary grid-cells”. Hence each primary face-grid gets a uniform resolution of  $90/n_g$  primary grid-cells per degree. In the legibility framework,  $n_g$  is taken as 90, making the resolution of each primary face-grid as 1° per cell for visibility computations. For making a variable resolution data-structure, within each primary grid-cell a new uniform face-grid is added which we refer to as the “secondary face-grid”. Each secondary face-grid consists of overlaid  $n_a^2$  grid-cells that act as secondary receptor surface in our legibility-framework. We refer to these grid cells as “secondary grid-cells”. Since, an increased resolution results in high memory consumption initially all secondary face-grids remain uninitialized to reduce memory usage. Based on the requirement, only specific secondary face-grids are initialized, as described in the 4.4. Fig. 7 illustrates the model of data-structure for the design of variable resolution cube-grid and Fig. 8 shows its pictorial representation. The values of  $n_a$  taken are same as for resolution shown in table 1. Using this scheme, a hierarchical variable resolution cube-grid is constructed without disrupting the primary uniformity. As an advantage, same cube-grid data structure can support both visibility-framework and legibility-framework. Being a common medium, it also increases the information transfer rate between the two frameworks.

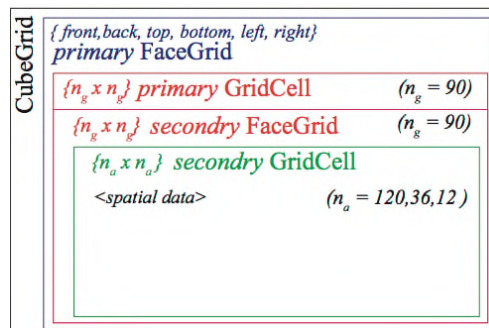


Figure 7 Variable resolution Cube-Grid data structure

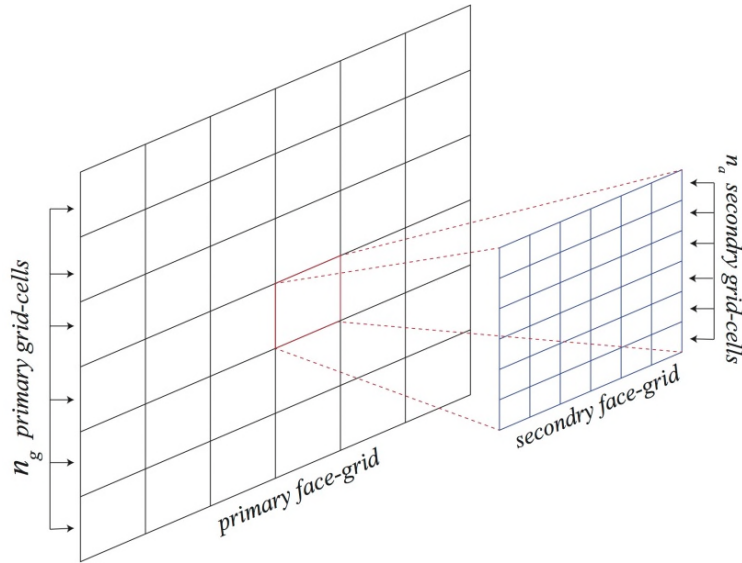


Figure 8 Pictorial representation of variable resolution Cube-Grid

#### 4.4 Sampling of visible spatial information

To compute the number of cells occupied by the projected object on the variable resolution cube-grid, the object is projected on the cube-grid with respect to its centre. The size of the projected image over the cube-grid varies with position and size of workspace object. For sampling of spatial information a two step procedure is applied. In the first step, projection of the object is taken over the primary face-grid containing  $n_g^2$  primary grid-cells, where visibility analysis is performed. The framework classifies primary grid-cells into two categories viz. “IN” and “OUT”. Cells named “IN” cells are the primary grid-cells occupied by projection of the object i.e. they are the cells containing visible spatial information and “OUT” cells are the cells where no visual information is projected. Line 1 to Line 5 in algorithm 1 describes the same step. In step two, only the specific primary-grid cells with spatial information, i.e. the “IN” classified cells are considered only for further sampling. For each “IN” classified cell, a secondary face-grid is initialized. The resolution of the secondary face-grid is chosen with respect to the position of its corresponding primary grid-cells in FoV. The framework then classifies the secondary grid-cells into two categories viz. “IN” and “OUT”. A variable named as “cellCount” is used to store count of secondary grid-cells classified as “IN” cells, that contain spatial information. Line 6 to Line 23 in algorithm 1 describes this step. Finally, as simulation output we get the number of secondary grid-cells occupied by the projection of object located in the spatial workspace of DHM.

**Input:** Object O  
**Output:** classified Cube-Grid A, count of cells-occupied as cellCount

```

1 initialize new FaceGrid data-structure as primaryFG of A;
2 set resolution of primaryFG = 90;
3 initialize new uniform-resolution GridCell data-structure as primaryGC;
4 project object O on primaryFG;
5 classify all primaryGridCell(s);
6 set cellCount = 0;
7 foreach primaryGC in primaryFG do
8   if primaryGC is not OUT then
9     initialize new FaceGrid data-structure as secondaryFG;
10    foreach secondaryFG in primaryFG do
11      if FoV range between CentralFoV then
12        set uniform-resolution of secondaryFG = 120
13      else if FoV range between MediumFoV then
14        set uniform-resolution of secondaryFG = 36
15      else if FoV range between PeripheralFoV then
16        set uniform-resolution of secondaryFG = 12
17      end
18      initialize new uniform-resolution GridCell data-structure as secondaryGridCell;
19      classify all secondaryGridCell(s);
20      update cellCount;
21    end
22  end
23 end

```

*Algorithm 1 Sampling of spatial information using variable resolution Cube-Grid*

#### 4.5 Qualitative Results and Observations

According to the Snellen acuity tests, text of size 1.8 cm shown at a distance of 1 m is easily recognizable by a person with acuity of 1.0 [20]. Based on this fact, a text line was projected on a variable resolution cube-grid and results were visually rendered. Fig. 9 shows the visual output of Cube-Grid for the sentence, "The quick brown fox jumps over the lazy dog." of height 1.8 cm, when shown at a distance of 1 m, where the point of fixation is at the first letter "T". The primary grid-cells are rendered with a white border. Text appearing in green is made up of secondary grid-cells that are classified as "IN". The blue background consists of secondary grid-cells that are classified as "OUT". Note that within  $0^\circ$  to  $2^\circ$  FoV region, since the resolution of secondary grid-cells is  $120 \times 120$  for each primary grid-cell, the text is sampled at a high resolution and hence it is legible. In the medium FoV region, from  $2^\circ$  to  $20^\circ$  the resolution of secondary grid-cells is reduced to  $36 \times 36$ , making the text a little mixed up. Beyond  $20^\circ$ , in the peripheral FoV region, the resolution of secondary grid-cells is reduced to  $12 \times 12$ , and hence the legibility of text is very low. The changing effect is noticeable in the letter "e" underlined in Fig. 9.

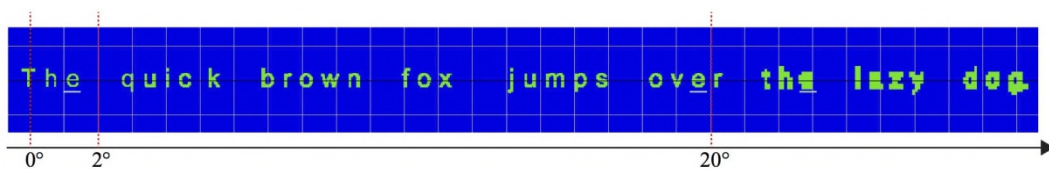


Figure 9 Visual output of Cube-Grid for the sentence, "The quick brown fox jumps over the lazy dog.", of height 1.8 cm, when shown at a distance of 1 m, where the point of fixation is at first letter "T"

## 5 Computational model for Quantitative Legibility Assessment

Human vision is a highly developed complex activity. It involves visual sensing, perception, and information acquisition in a synergistic manner. For visual performance modelling in DHM, a simplified and structured approach is proposed here which would enable systematic analysis of a visual scene. In humans, the ability to perceive an object depends on its projected area in the central FoV along with the ability to identify some specific features that visually aid in task performance. These features are referred as “salient features” in this paper. For viewing any object, first the size and position of a salient feature should be chosen such that it covers appropriate retinal area necessary for detection [17]. Secondly, to aid in its recognition the salient feature should be visible at highest resolution in the central FoV (Covert Selection) [44]. And thirdly, the object should be focused properly by the visual system without much strain [46]. In the present work visual performance is modelled in line with the conventional ergonomics such as visibility, acuity, accommodation, legibility and readability. However, since these terminologies are well understood for the textual stimulus, it is not easily definable for generic and visual stimulus containing objects of varying shapes and sizes in an unstructured environment and lighting.

We developed an analogical definition of legibility using the concept of features to extend the concepts of text into the domain of geometric objects. As discussed by Cornog et. al. [12] and McCormick et. al [27], legibility is the attribute of characters that distinguish each one from others by the features such as stroke width, height-to-width ratio, fonts and form of characters. These determine the speed and accuracy of tasks like reading or identifying the characters. In case of objects, similar attributes can be defined by providing its affordance characteristics [22] i.e. several distinguishable salient features present in an object that visually aids an operator performing a task [39, 24]. If projection of a feature is large enough onto central FoV region, the object is said to legible. On the other hand its legibility will reduce if the projected area is very less or if it is very large such that it goes beyond central FoV.

For instance, a screw can be defined as an object that is combination of a flat screw-head with a slot and a helical threaded shaft. The screw-head allows it to be turned using a screwdriver such that the threaded-shaft acting as an anchor goes inside the surface. Here the screw-head acts as a visual salient feature of the screw that aids its legibility while performing a task. At any given task configuration, the size and distance of the screw-head will help in determining its overall legibility. Hence, in general an object can be said to be legible if the highest resolution detail of its salient features is visually available to the operator. To take these facts in account we have associated the following three indexes to be computed for each salient feature that will help in evaluating legibility.

### 5.1 Index of Acuity

Based on the definition of acuity in section 4.1, any object can be classified as legible if it occupies a minimum number of grid-cells over the cube-grid. The required minimum number of cells can be pre-calculated based on object dimensions and size of its salient features. In the current framework, as an input, user provides a view dependent, “standard configuration” that best suits a given task to DHM as an initial calibration step. Based on this configuration, the framework takes the number of occupied secondary grid-cells i.e. “cellCount” as the number of receptor-cells ( $n_{cells-occupied}$ ) and stores it locally (in program memory). It serves as the threshold value required to quantify minimum size requirements for a given object. Index of Acuity is defined as the number of cells mapped by an object ( $n_{cells-occupied}$ ) at any given configuration divided by minimum number of cells computed at standard configuration ( $n_{cells-required}$ ). For any resolution in the FoV, if number of cells projected is less than



$n_{cells-occupied}$  then object is likely to be less detectable and hence less legible. More than required number of cells will not affect the legibility since the size of object is larger than the minimum threshold. Equation 1 is used to calculate Index of Acuity ( $\alpha$ ).

$$\alpha = \frac{n_{cells-occupied}}{n_{cells-required}}, n_{cells-occupied} < n_{cells-required}$$

$$= 1.0, otherwise \quad (1)$$

## 5.2 Index of Saliency

On the retinal surface, since the central FoV has the highest resolution, the focused salient feature has to be projected on the fovea to be perceived at the highest resolution. If size of the projected object is very large such that the area covered by its salient feature goes beyond the central FoV, visual details of feature are lost. This reduces the legibility. To take care of this, legibility-framework relies on an Index of Saliency ( $\delta$ ) defined on the basis of cells occupied by the salient feature projected on Cube-Grid. A normalized summation of acuity values of corresponding FoV regions are taken as weights of cells occupied to determine  $\delta$ . In this model, the acuity value of eccentricity from the centre of the fixation is directly used as a weighting factor for calculating the saliency value of the feature. Weight of occupied cells in central, medium and peripheral FoV is taken as 1.0, 0.3 and 0.1 respectively. If the salient feature occupies central FoV completely,  $\delta$  will be 1.0. With increase in size, as it starts to cover medium and peripheral FoV  $\delta$  will start to reduce. Equation 2 is used to calculate Index of Saliency ( $\delta$ ) for a given configuration.

$$\delta = \frac{\sum_{i=1}^{n_{cells-occupied}} w_i}{n_{cells-occupied}} \quad (2)$$

$\forall w_i$  is the weight of cell  $i$

## 5.3 Index of Accommodation

Accommodation refers to changing the shape of the lens in the eye to properly focus the image on the retina. In other words, accommodation is the ability of the eye to focus on objects at different distances. For example, the ability to read signs on the side of the road is an example of far vision. The ability of a control room operator to view a monitor display is an example of near vision. However, there is a near fixation distance inside which the eyes cannot effectively accommodate. This limiting distance is termed the near point of accommodation (NPA) that varies with population and age [25]. Objects closer than NPA appear blurred and hence the details are not easily seen. This factor is especially important while working with precision objects with very small size. NPA for population aged between 30-40 years is 25 cm [6]. It is taken as standard in the model however it can be customized based on different subjects. For addressing this factor, we have associated an accommodation index  $\lambda$  for an object axially located at distance  $x$  from the centre of the cube-grid defined in equation 3.

$$\lambda = \sqrt{\frac{x}{NPA}}, 0 < x < NPA$$

$$= 1.0, otherwise \quad (3)$$

## 5.4 Legibility Index Computation

For simulation and validation of precision tasks, in this paper we have limited our scope by incorporating following three main factors that affect legibility of any given operator object task configuration:

- i. *Size* - Object must be close enough to be seen clearly by operator; this is defined by  $\alpha$  in equation 1.
- ii. *Features* - For performing any task, a required salient-feature of object must appear in operator's central FoV; this is defined by  $\delta$  in equation 2.
- iii. *Distance* - In order to focus properly without strain object should not come closer than near point of accommodation; this is defined by  $\lambda$  in equation 3.

Since all the three factors are independent of each other, the model computes legibility index ( $\Gamma$ ) of particular task configuration using equation 4.

$$\Gamma = \alpha \cdot \delta \cdot \lambda \quad (4)$$

## 6 Vision Simulations and Results

### 6.1 Using Snellen Optotype

#### 6.1.1 Methodology

To simulate and verify the variable sampling based legibility framework, a common and internationally accepted method of measuring visual acuity was employed using Snellen Optotypes. These are the alphabets designed specifically to evaluate acuity of humans. Each optotype consist of an alphabet drawn on a 5x5 square-grid with a stroke width of 1 grid-cell. Since the resolving power of humans with an acuity of 1.0 at central vision is  $(1/60)^\circ$ , the size of grid is chosen such that each cell of the square-grid occupies  $(1/60)^\circ$  area in FoV and overall grid occupies  $5 \times (1/60)^\circ$  area. Since its an angular measurement of size, the height of optotype would depend on the distance of projection. For a standard population with an acuity of 1.0, these optotypes will appear legible if they occupy a minimum area of  $(5/60)^\circ$  in the central FoV. Any reduction in area either due to variation in distance or size would lower the legibility. For a projection distance of 100 cm, the size of each cell in the square-grid comes around 0.035 cm and 0.18 cm respectively. Based on this fact, CAD model of letter E was designed having height of 0.18 cm and corresponding stroke width of 0.035 cm Fig. 16(a).

#### 6.1.2 Simulations

As "standard configuration" input, the model of E was presented to DHM at a distance of 100 cm (Fig. 10). For this configuration, number of cells occupied by Cube-Grid were taken as  $n_{cells-required}$  for computation of  $\alpha$  using equation 1. NPA required for computation of  $\lambda$  using equation 3 was taken as 25 cm. the following two sets of simulations were performed using this Optotype:

- Set 1: To simulate the effect of variation in distance of head with respect a fixed size object on legibility, the axial distance of DHM head with respect to optotype along the line of sight was varied from 1 cm to 400 cm at fixed intervals. For each configuration  $\alpha$ ,  $\delta$ ,  $\lambda$  and  $\Gamma$  were computed using equations 1, 2, 3 and 4. The results are discussed in 6.1.3.
- Set 2: To simulate the effect of variation in size of object with respect to head at fixed position on legibility, the height of the E was varied from 0.18 cm to 90 cm at fixed intervals. For each configuration  $\alpha$ ,  $\delta$ ,  $\lambda$  and  $\Gamma$  were computed using equations 1, 2, 3 and 4. The results are discussed in 6.1.3.

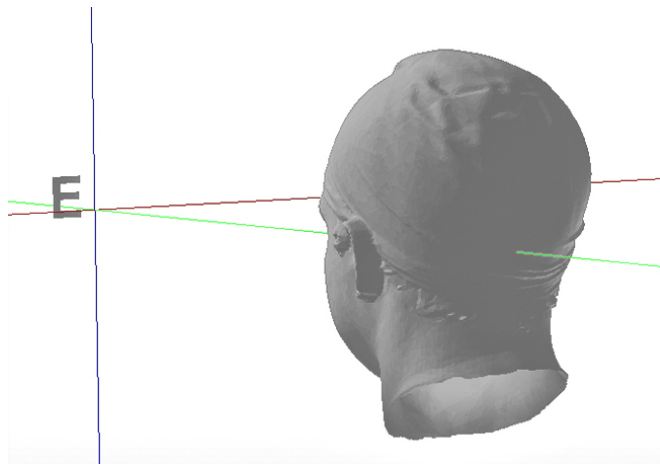


Figure 10 Task configuration for section 6.1: DHM head and Optotype E

### 6.1.3 Results of simulations

• Set 1: Variation of  $\alpha$  - Fig. 11 shows the variation of  $\alpha$  with distance.  $\alpha$  is 1.0 for the distances nearer than “standard configuration” distance of 100 cm since projection of optotype occupies more cells as compared to standard configuration. As the head starts to go farther than 100 cm, the subtended angle over central FoV reduces and hence number of occupied cells also reduce and  $\alpha$  starts to reduce.

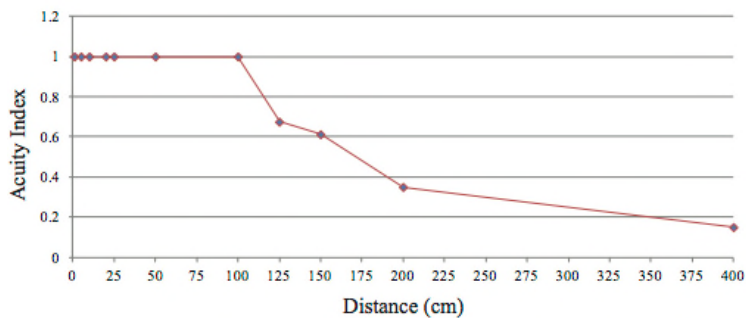


Figure 11 Variation of Index of Acuity with distance for Optotype E of fixed size of 1.8 mm

• Set 1: Variation of  $\delta$  - Fig. 12 shows the variation of  $\delta$  with distance.  $\delta$  is 1.0 for distances nearer than the standard configuration distance of 100 cm. The subtended angle by E increases as it comes nearer. At the point where the subtended angle goes beyond the central FoV,  $\delta$  starts to reduce. This effect can be noticed more clearly in results of Set 2.

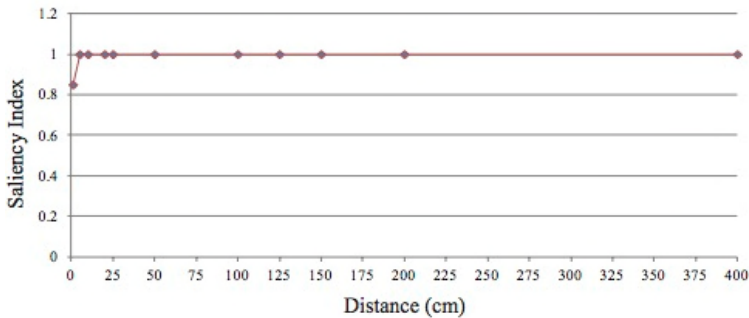


Figure 12 Variation of Index of Saliency with distance for Optotype E of fixed size of 1.8 mm

• Set 1: Variation of  $\lambda$  Fig. 13 shows the variation of  $\lambda$  with distance.  $\lambda$  is 1.0 for distances greater than 25 cm, the standard assigned value of NPA. As the letter starts to come nearer than NPA,  $\lambda$  starts to reduce.

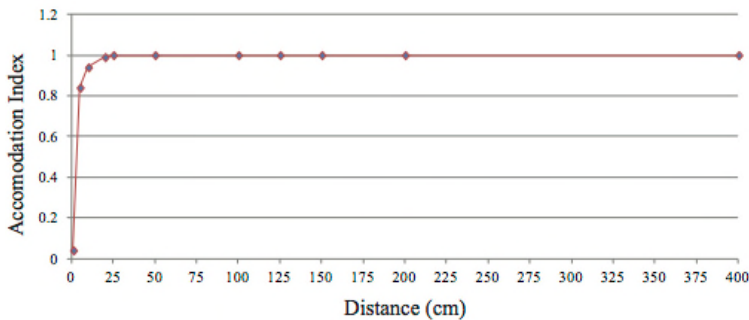


Figure 13 Variation of Index of Accommodation with distance for Optotype E of fixed size of 1.8 mm

• Set 1: Variation of  $\Gamma$  Fig. 14 shows the variation of  $\Gamma$  with distance. For distance closer than 100 cm,  $\alpha$  remains at 1.0 but Letter E subtends an angle greater than limits of Central FoV hence  $\delta$  and  $\lambda$  change. From 10 cm to 25 cm, the subtended angle is within the range of central FoV hence  $\delta$  becomes 1.0.  $\Gamma$  varies only with  $\lambda$ . From 25 cm to 100 cm since all indexes remain at 1.0, the  $\Gamma$  stays at 1.0. Beyond 100 cm the size of E starts to reduce and hence  $\Gamma$  dependent only on  $\alpha$  starts to reduce.

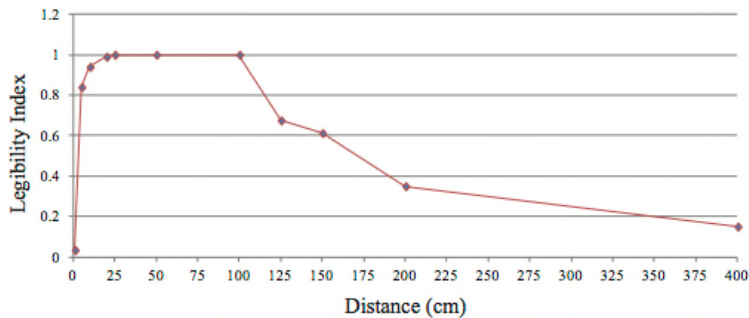


Figure 14 Variation of Index of Legibility with distance for Optotype E of fixed size of 1.8 mm

• Set 2: Variation of  $\Gamma$  In this set, since the simulations were performed at a fixed distance of 100 cm and minimum size of optotype is 0.18 cm,  $\alpha$  and  $\lambda$  remain constant at 1.0. At each configuration  $\delta$  and  $\Gamma$ , which is purely dependent on  $\delta$  is computed. Fig. 15 shows the variation of  $\delta$  and  $\Gamma$  with size. From the height of 4 cm, the angle subtended by E starts exceeding central FoV and hence a drop in  $\delta$  and  $\Gamma$  value is seen.

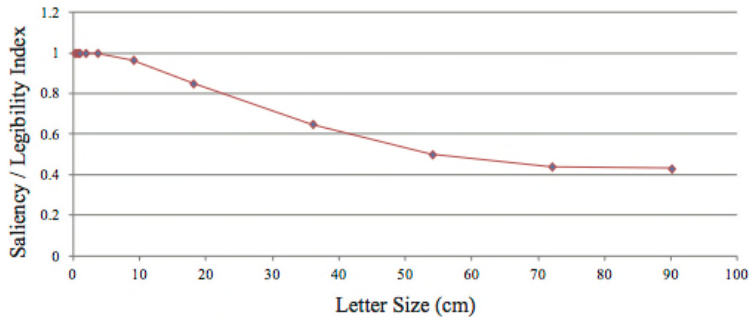


Figure 15 Variation of Index of Saliency and Index of Legibility with size of Optotype E at fixed distance of 100 cm

## 6.2. Task simulation using an object in workspace

### 6.2.1. Methodology

The most common task in any given workspace is a screw-fastening task and is considered as a case for simulation using legibility-framework. Based on the utility, screws come in different shapes, sizes and slots. They generally have a slot on the screw-head that allows for it to be turned. It also allows an operator to choose the respective tool for fastening. Both these activities heavily depend upon active visual feedback to the operator. Hence as a basic requirement the screw-head must be visible and legible to the operator involved in a fastening task. For the purpose of simulation, a CAD model of Pozidriv screw-head is considered [29]. A Pozidriv screw head is most often confused with Philips screw-head since both have four-slot design. But only upon closer visual examination can they be differentiated. Pozidriv screw head comes with a second set of cross-blade slots at the root of the large slots. For “standard configuration”, size of the screw head was chosen such that width of the second set of cross-blade slot occupies  $(1/60)^\circ$  area in FoV. For a projection distance of 100 cm, the size of screw-head comes around 3 cm (Fig. 16b).

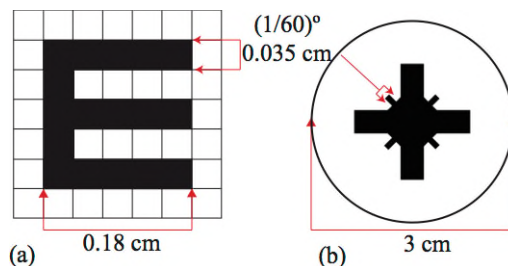


Figure 16 (a) Dimensions of Optotype E (b) Dimensions of pozidriv screw-head

## 6.2.2 Simulations

As “standard configuration” input, the model of the screw-head was presented to the DHM at a distance of 100 cm. For this configuration, number of cells occupied by Cube-Grid was taken as  $n_{cells-required}$  for computation of  $\alpha$  using equation 1. NPA required for computation of  $\lambda$  using equation 3 was taken as 25 cm. To simulate the effect of variation in distance of head with respect to a fixed size object on legibility, the axial distance of DHM head with respect to screw was varied from 1 cm to 400 cm and  $\Gamma$  at each configuration was computed using equation 4. The results are discussed in 6.2.3.

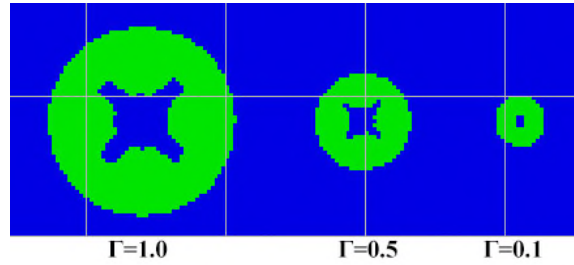


Figure 17  $\Gamma$  and Visual Output of Cube-Grid for screw of size 3 cm shown at the distances of 100 cm, 150 cm and 300 cm

## 6.2.3 Results of simulations

Fig. 17 shows computed  $\Gamma$  and the qualitative visual output of the surface of the cube-grid, shown at the distances of 100 cm, 150 cm and 300 cm. Fig. 18 shows the variation of  $\Gamma$  as the distance of the screw is varied from 1 cm to 400 cm. For the distance less than 25 cm, the screw head is not focusable and it subtends an angle greater than central FoV. Hence  $\Gamma$  in this region varies with  $\delta$  and  $\lambda$ . Beyond 25 cm;  $\lambda$  remains at 1.0 since the distance of object is more than NPA and hence is always focusable. From 25 cm to 50 cm the subtended angle is still greater than central FoV but object is focusable hence  $\Gamma$  in this region varies only with  $\delta$ . Beyond 50 cm, the subtended angle comes in the limits of central FoV and hence the value of  $\delta$  remains at 1.0. From 50 cm to 100 cm the object remains fully legible since all three  $\alpha$ ,  $\delta$  and  $\lambda$  are at 1.0. Beyond 100 cm the size of screw starts to reduce such that its details are not clearly visible and hence  $\Gamma$  now dependent only on  $\alpha$ , starts to reduce.

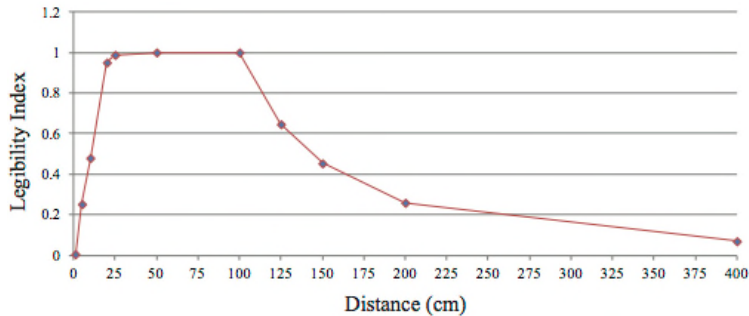


Figure 18 Variation of Index of Legibility with distance for Screw of fixed size of 3 cm

## **7 Discussion**

visDHM provides both qualitative and quantitative approaches for visual analysis. In current approach entire FoV is divided into three regions for analysis. But based on requirements the regional distributions as well as required resolutions for secondary grid-cells can be modified. In [47], Watson proposed a formula that correlates human retinal cell receptive field density with FoV that can be mapped in the framework to provide more accurate representation. The framework is extensible to any kind of functional visual assessment, although only a limited aspect is presented in current work. Legibility of an object for an operator depends on two external factors viz. object salient features and standard configuration. First, the salient features that will vary with context of task and hence it should be entered manually to the framework. Second the “standard configuration” will vary with respect to viewpoint of operator. Designer as input to the framework will provide these. Hence the index of legibility will vary with object, operator and task. Using this framework, several key aspects for designing vision friendly products can be addressed that are discussed as follows.

### **7.1 Designing products based on individual’s visual requirements**

This framework provides an alternative way of representing individual’s visual information for designing products. The multi resolution grid and various indexes used computation of legibility index can be used for simulating normal as well as impaired vision leading to inclusive design of products. For instance, changing distribution of grid cells and index of acuity can simulate defects like low acuity vision. Modifying weights used in index of saliency can simulate cataract and other retinal defects. Changing accommodation index can simulate refractive errors. With an advent of computers and wearable devices, the design of typefaces and visual display and interaction interfaces has become a subject of considerable interest. This framework opens new possibilities of helping the designers for designing such products.

### **7.2 Visual Workspace Simulations**

Poorly designed products or improper workspace design generally cause visual discomfort. According to a study conducted by Sen and Richardson in 2007, nearly 60 million people suffered from computer vision syndrome (CVS) globally and about one million new cases occur each year [37]. The distance of the computer monitor from the human eyes has been shown to be an important risk factor for CVS because the closer the eyes to the monitor the more difficult the eyes have to work to accommodate with it. Researchers have recommended a viewing distance between 30 and 70 cm as measure to reduce visual symptom [42] however they are primarily dependent on individual’s visual characteristics and resolution of computer monitor. In [3] we have shown that in case of manual assembly, observed that as long as components remained properly visible and within hand reach, the subjects were able to perform faster at a longer visual distance. Similarly tasks involving precision activities like electronic assembly and medical procedures are prominently dependent on visual information processing. Thus, fatigue and postural fixation have been the matters of concern for such activities [34]. Application of DHMs for simulation of such tasks is not yet available. With a primary objective to minimizing lead time and improving total assembly cost, methods like Manual Design Efficiency by Boothroyd [5], Design for Assembly Calculator by Sturges [21], MTM, MODAPTS, MOST [15] have been designed for the prediction of assembly time and simplification of manual assembly. They have been targeted for the optimization of trivial shop floor assemblies like material handling and lifting weight. Many of them rely on some form of Fitts Index of difficulty (ID) as given in Fitts’ law that classify any manual task on the basis of distance

travelled by hand and size of target [26]. However these methodologies may not work in the case of precision activities since movement, speed and accuracy of hand relies mostly on visual feedback. Using the presented framework behavioural simulation models can be developed and actual human validations can be conducted.

## 8 Conclusions

In this paper we have presented a visDHM, a functional vision framework that is capable of performing human visual acuity based central, mid and peripheral FoV based system simulations by relying on newly developed variable resolution Cube-Grid. For legibility assessment, this framework takes into account several human and object dependent visual parameters that can be personalized for different subjects and workspace objects. Based on these human and object centric parameters, the sampled information is analysed by framework and a numerical value representing legibility-index is computed. The index varies between 0.0 (low) to 1.0 (high) representing legibility of an object for a given human and workspace configuration. A functional implementation has been demonstrated using an optotype and a workspace object. The simulations show changes in legibility index of particular configuration by varying object's size and distance with respect to operator's acuity and accommodation limits. The result obtained by legibility-framework for the simulations has been discussed. In this presented work we have tried to answer the questions raised in section 1 by the method of human-in-loop simulations. The examples presented in section 6 show that this framework can be used for modelling objects usable for human vision requirements, identifying target population for using a product and simulating visual behaviour of humans for any given product. The applications of which are discussed in section 7. The present framework is limited to functional visual characteristics like field of vision, acuity and accommodation. The developed approach is purely geometric and spatial factors like object illumination, recognition and location are not modelled and kept for future work. Additionally for simulation purposes, we have considered a head with single eye. For binocular vision modelling, combining two such frameworks is required that can make it possible to simulate depth perception based behavioural analysis. It would be interesting to simulate this model along with whole body inverse kinematics based postural human model (like JACK) in order to achieve natural behavioural simulations.

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## **International Journal of Design Sciences and Technology**

**Design Sciences, Advanced Technologies and Design Innovations**

*Towards a better, stronger and sustainable built environment*

### **Aims and scope**

Today's design strongly seeks ways to change itself into a more competitive and innovative discipline taking advantage of the emerging advanced technologies as well as evolution of design research disciplines with their profound effects on emerging design theories, methods and techniques. A number of reform programmes have been initiated by national governments, research institutes, universities and design practices. Although the objectives of different reform programmes show many more differences than commonalities, they all agree that the adoption of advanced information, communication and knowledge technologies is a key enabler for achieving the long-term objectives of these programmes and thus providing the basis for a better, stronger and sustainable future for all design disciplines. The term sustainability - in its environmental usage - refers to the conservation of the natural environment and resources for future generations. The application of sustainability refers to approaches such as Green Design, Sustainable Architecture etc. The concept of sustainability in design has evolved over many years. In the early years, the focus was mainly on how to deal with the issue of increasingly scarce resources and on how to reduce the design impact on the natural environment. It is now recognized that "sustainable" or "green" approaches should take into account the so-called triple bottom line of economic viability, social responsibility and environmental impact. In other words: the sustainable solutions need to be socially equitable, economically viable and environmentally sound.

IJDST promotes the advancement of information and communication technology and effective application of advanced technologies for all design disciplines related to the built environment including but not limited to architecture, building design, civil engineering, urban planning and industrial design. Based on these objectives the journal challenges design researchers and design professionals from all over the world to submit papers on how the application of advanced technologies (theories, methods, experiments and techniques) can address the long-term ambitions of the design disciplines in order to enhance its competitive qualities and to provide solutions for the increasing demand from society for more sustainable design products. In addition, IJDST challenges authors to submit research papers on the subject of green design. In this context "green design" is regarded as the application of sustainability in design by means of the advanced technologies (theories, methods, experiments and techniques), which focuses on the research, education and practice of design which is capable of using resources efficiently and effectively. The main objective of this approach is to develop new products and services for corporations and their clients in order to reduce their energy consumption.

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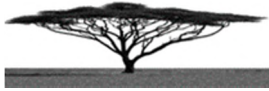
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