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RESEARCH ARTICLE

Reducing VR Sickness by Directing User Gaze to Motion Singularity Point/Region as Effective Rest Frame

MU-HYEON PARK, KWAN YUN, AND GERARD J. KIM
Department of Computer Science and Engineering, Korea University, Seoul 02841, Republic of Korea
Corresponding author: Gerard J. Kim (gjkim@korea.ac.kr)

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ABSTRACT Simulation sickness is one major obstacle in proliferation of virtual reality. The sensory mismatch between the visual and vestibular senses about user motion is attributed as the main cause. One effective method has been the use of the rest frame, which refers to the reference object that remains fixed in position with respect to the user. A popular choice of the rest frame is the virtual nose, but it can direct one's attention away from the main part of the navigation content. We propose to instead use the area within the screen space that represents the least amount of motion in the navigation content, called the Motion Singularity Point/Region (MSP/R) as such a rest frame. Viewing such a region is thus expected to reduce the sensory conflict and ensuing sickness. Such a region can be found by analyzing the content with respect to motion and estimating the region(s) of the image space with the least relative amount of the total optical flow. We experimentally validated the VR sickness reduction effect of looking at the MSP/R compared to that of the virtual nose. In addition, we confirmed that the content agnostic MSP/R to be much coinciding with the user's natural viewing direction, making it less distracting from the main content. This makes the MSP/R a more practical and viable rest frame object for sickness reduction than the virtual nose.

INDEX TERMS Virtual reality, motion sickness, simulation sickness, VR sickness, vection, navigation, optical flow, rest frame, motion singularity, focus of expansion.

I. INTRODUCTION

Sickness remains to be one of the major hurdles in the widespread use of virtual reality (VR) [1], [2]. The two most prevalent hypotheses behind VR sickness are the sensory mismatch and rest frame theories. The former attributes VR sickness to the conflicting user motion information as interpreted by between the visual and vestibular senses [1], [2], and the latter, to the absence of reference object(s) (portions of the virtual environment that remain fixed in relation to the user) for helping the user maintain one's sense of balance and awareness to the ground (or gravity) direction [3], [4] [5]. Moreover, fixating on such unmoving objects is likely to reduce the sensory mismatch as well by, reducing the visual motion information. However, the rest frame may not blend naturally into, and be intrusive to, the original content. One popular method to reduce VR sickness is the inclusion of the virtual nose, whose effect can be explained according to the aforementioned rest frame theory, and furthermore supports the possibility that a rest frame may not necessarily have to be explicitly ''grounded'', but be simply non-moving with respect to one's body. Among many possible rest frame objects, the virtual nose is special, because, aside from being content-agnostic and familiar,

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it lies just slightly off the central visual field. Previous work have reported that, along with the sickness reduction effect, the virtual went mostly unnoticed despite the substantial occupance in the screen space [4], [6], [7] - the question remains as how it would fare with regards to content intrusion compared to when the virtual nose is absent.

Such an observation has inspired us to consider the motion singularity point/region (MSP/R) as an alternative and effective rest frame. The MSP/R refers to the point/region where there is no or little (under some preset threshold) amount of motion information in the screen space (also known as the stationary point in other literature [7]). One way to assess the motion information in the screen space is to compute the optical flow between consecutive image frames. The optical flow roughly represents the projection of relative movements of the main feature points in the content. Further analysis can identify the region where there is little or even no relative motion (or optical flow). For example, in pure forward motion, the MSP is seen as the vanishing point of the radially outgoing optical flow. In fact, this point represents the direction (or infinite destination) of the forward translational motion of the user. In this particular case, it coincides with the "Focus of Expansion (FOE)" [8]. FOE refers to the point where optic flow is absent and seems to come from. However, if there is rotation, the FOE may not coincide with the MSP. While MSP is theoretically a point, by the nature of motion, its vicinity also contains relatively less amount of visual motion. There is also research that indicates that humans are naturally drawn to sustain attention to the singularity/FOE point during navigation [9]. Since MSP or its vicinity, contains little motion information, we project that looking or fixating on it would cause less sensory conflict with the vestibular sense. As it exists in any navigation content, and even naturally draws attention (i.e not a distraction factor) indicated minimally (just a point) virtually without any occlusion to the content, we posit it to be an excellent candidate for a rest frame object for reducing the extent of the VR sickness.

In this paper, we first present a simple way to identify the point or region of the motion singularity based on the optical flow analysis. The identified point or region is overlaid in a simple fashion e.g. as a small dot and indicates the Motion Singularity Point Region (dubbed as MSP/R hereon) centered around the MSP as the rest frame. Even if the MSP/R may overlap much with the region where the user is likely to see anyway, its explicit indication will be helpful as a reminder to direct one's attention to it in the event of sickness symptoms felt. We conduct an experiment to validate its basic effect of reducing VR sickness as compared to the condition without any provision for sickness reduction, and also assess its relative advantage, if any, to the other popular method, the virtual nose. We hypothesized not only of the significant VR sickness reduction effect of MSP/R, but also the less intrusion into the content and degrading of the navigational experience (e.g., presence and immersion) as compared to the case of using the virtual nose.

The contributions of this research are summarized as follows:

- The new Motion Singularity Point/Region (MSP/R) is newly proposed herein as a viable rest frame object that has significant sickness reduction effect and minimal content intrusion and immersive experience degradation.
- A simple real time algorithm is devised to estimate the MSP/R.
- The extent of sickness reduction and content intrusion is compared to and evaluated against one of the most popular rest frame object (for sickness reduction), the virtual nose.
- The rest frame theory of sickness reduction is also postulated in term the regulation of the visual motion regularity level.

II. RELATED WORK

VR sickness refers to the discomforting symptoms arising when using immersive VR simulators, especially with navigating contents. Major symptoms include disorientation, headache, nausea, and ocular strains [1]. Among various possible causes, VR sickness is primarily explained by the aforementioned sensory mismatch theory [1], [2]. Few approaches such as the dynamic field of view adjustment [10] and image blurring during rotation [11], [12] (and similarly foveated rendering [13]) are common in their attempts to reduce the visual motion information and thereby the extent of the sensory mismatch [14]. Mixing in motion trails reverse to the visual motion to counterbalance the sense of vection has been suggested as well [15]. Another explanation to the motion (or VR) sickness is provided by the postural instability theory [16]. According to this, sickness can occur with prolonged postural instability. In fact, regardless of the sickness, VR users often exhibit varying degrees of postural instability by visual motion [17]. While the exact cause is not well understood, it could be related to the effect of the aforementioned rest frame, which is helpful to VR users maintain one's balance [3], [4]. Ebenholtz et al. also suggested the possible role of the excessive eye movement in causing postural imbalance and motion sickness [18] - fixating on the rest frame object to eventually ease such sickness.

In fact, optical flow has been extensively investigated in relation to self-motion and motion sickness. Visual motion itself is perceived through the detection of optical flow and quantified by its amount, as first discovered by Gibson [19]. In follow-up studies, methods have been devised to modulate the degree or characteristics of vection by manipulating the optical flow form [20], overlapping different directional/rotation flows [21], and mixing in visual noise [22]. Moreover, the human brain can differentiate between the visual motion caused by oneself and those caused by objects in the visual field, particularly when facilitated by the vestibular sense [23]. However, adopting these approaches to modulate visual motion (and sickness) can intrude into the original content. We propose instead to leave the original content intact and direct one's attention to the region with the least motion information (e.g., FOE or MSP), even if the sickness reduction effect might be comparatively less.

Several FOE/singularity finding algorithms based on optical flow analysis have been proposed [24], [25]. Many of them have the ultimate objective to reversely infer the exact user motion, and as such may involve complicated mathematical formulations and time-consuming optimization [26]. Other works looked at clustering the motion/optical flow vectors in the motion video to only identify distinct moving or stationary objects [27] (an approach also adopted in this paper). While we consider adopting some of these approaches for robustness and correctness in the future, for now, we use a simple method for a rough estimate of the MSP from the directions of the optical flow field as suggested in [28].

III. ESTIMATING MOTION SINGULARITY POINT AND REGION (MSP/R)

A. BASIC ALGORITHM AND PERFORMANCE

As previously stated, the estimation of the MSP starts with generating the optical flow field of the nominal visual features in consecutive image frames. Thus such features are first extracted using the Shi-Tomasi corner detectors [29]. We considered the common assumption that the motion is typically not drastic and the images are mostly similar between two consecutive frames. The Lucas-Kanade's fast optical flow algorithm [30] is applied to estimate the feature movements and their correspondences. Corresponding moving features constitute the optical flow vectors, which are extended as infinite lines. The intersections of these infinite lines are computed, and the grid region (at a pre-determined resolution) with most intersections is found, and within this grid, the average positions of the intersection points are computed as the estimated MSP (see Fig. 1). MSR is simply a small region centered around the MSP, whose extent will not be discussed in depth. If the user sustained one's attention to the MSP, the MSR would be subtended approximately by the extent of the foveal region.

We conducted a simple accuracy test of the proposed algorithm. The test was conducted for three cases of apparent motion - (1) pure forward, (2) forward with pitch rotation, and (3) forward with yaw rotation. The three motions were presented using the Space exploration content with the algorithm computing the MSP. The computed MSP was compared to the ground truth singularity point location, which would be known as the motion parameters were fixed. For instance, forward motion with yaw rotation would have the ground truth singularity point in the left or right middle region of the screen space. The average pixel differences (on a display with the resolution of 1920 $\times$ 1080) to the ground truth and the hit percentages (when computed coincided with the ground truth) were: (1) pure forward - 99 (89% hit), (2) forward with pitch rotation- 15 (87% hit) and (3) forward with yaw rotation - 12 (83% hit). The heat map in Fig. 2 illustrates the performance. As our purpose was to provide a rough estimate just of the ''region'' of motion singularity, the algorithm was deemed sufficient for validating the effectiveness of the MSP/R in reducing the extent of the VR sickness.

Fig. 2 illustrates the accuracy with heat maps. Note that the highest accuracy was achieved for the case of the pure forward motion, but simulation with the Space navigation content produced some noisy output resulting in the higher average pixel difference. Such artifacts can be reduced by employing data filtering.

B. EXCEPTIONAL CASES

However, the proposed algorithm is not general enough to cover all types of virtual motion such as pure side-way translation or pure rotation - such motions without radial optical flow pattern are treated separately. In the case of side-way motion, MSP may not exist at all (or exist at infinity), and the MSP is put at the far middle end in the direction of the flow (or simply not indicated) (see Fig. 3). As for the case of pure roll rotation, MSP may be found by looking for the center of the rotational optical flow. If the blind intersection method was applied, many potential candidates would appear as shown in Fig. 3-middle, and the center of rotation can be estimated by their average. Lastly, the optical flow pattern for yaw rotation looks radial if the directions were ignored, resulting in placing the MSP where the red dot is. Additional analysis with regards to the distribution of the optical flow vector directions can place the MSP where the blue dots are (either). Also note that pure side-way or roll motions are rare in common VR navigation. In addition, in the case, visual features do not exist (such as in texture-less walls and cloud-less sky), such regions should be computed also as containing the MSP. For now, we only compute for the MSP from the optical flow field in the feature-rich regions.

C. APPLYING MSP/R TO VR CONTENT

In our current approach, the MSP/R is estimated based on the 2D optical flow analysis, and overlaid in the screen space. Therefore, it is applicable to the video based (e.g. 360 degree immersive video), or mono 2D rendered (source not available) 3D graphic VR. However, for the case of stereoscopic rendering, as there are two imagery (left and right), an additional method to make sure the MSPs found in the left and right images match exactly so that it can be perceived in focus.

For stereoscopic 3D graphic VR content whose source is available (which is demonstrated in this work), in addition to the two virtual cameras (for left and right), we use another ''middle'' camera (located between those of the left and right) whose projected image (but not rendered) is used for the input to the proposed algorithm. The MSP found in the middle camera is overlaid in the left and right images by coordinate transformation. One limitation of this method is that the middle camera can only cover the space overlapped by those

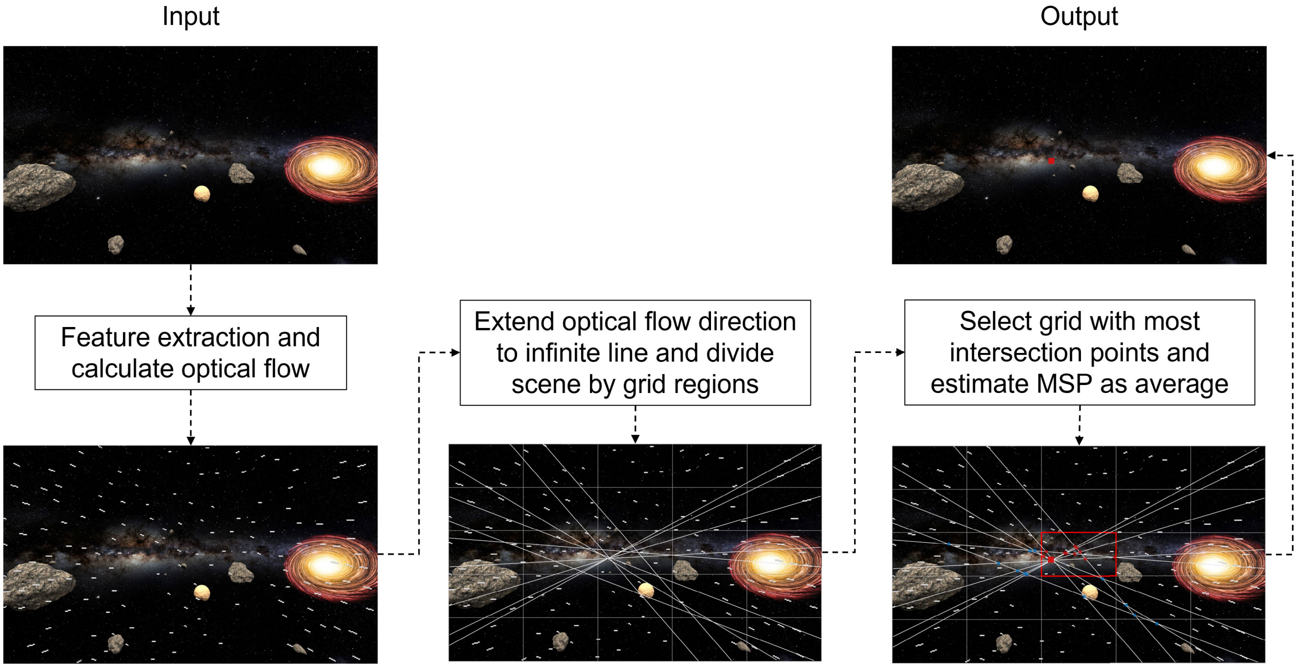


FIGURE 1. The algorithm flow for estimating the Motion Singularity Point(MSP) as the collective intersections of the optical flow orientations (shown as short/long white line segments).

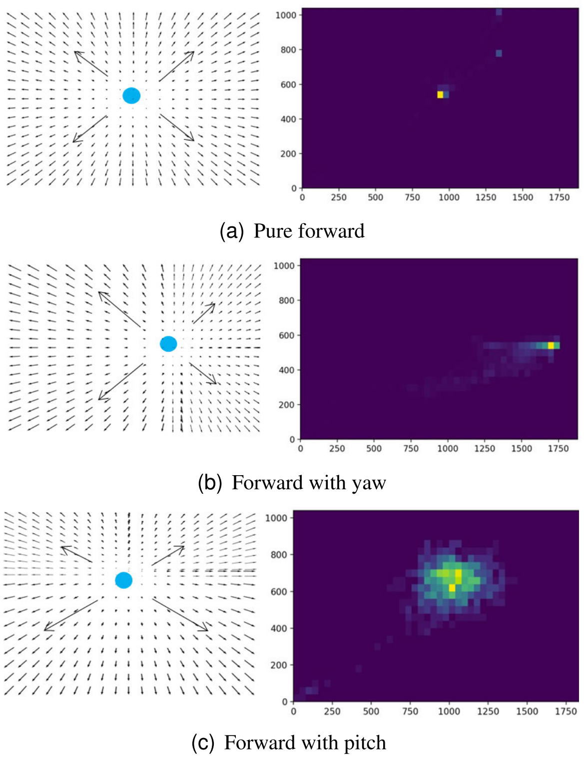


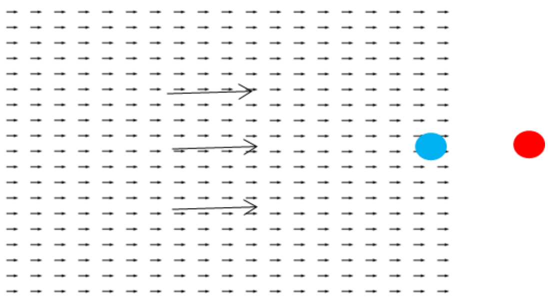
FIGURE 2. Heat maps illustrating the accuracy of the MSP estimation with respect to the ground truth (yellow dot) for three types of typical motion in the Space navigation content. Also illustrated are the optical flow patterns and where MSPs are placed by the intersection approach.

of the left and right, rather than the entire stereoscopic visual field. An alternative method might be to analyze the known user motion (as the source is available, for either fixed or interactive navigation) and identify the MSP in the 3D space (and project it to the left and right screen spaces). Fig. 4 shows the MSP overlaid on the VR content using the proposed application method and the virtual nose approach. Again, we emphasize that, despite the simplicity of the proposed algorithm and some of its apparent limitations, the objective of this work is to validate the effectiveness of the MSP/R in reducing the extent of the VR sickness for which the current implementation was sufficient for the test experimental contents. A more general and refined algorithm remains as future work.

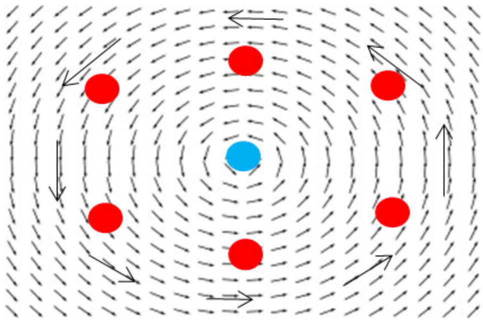
IV. VALIDATION EXPERIMENT

A. EXPERIMENTAL DESIGN AND TASK

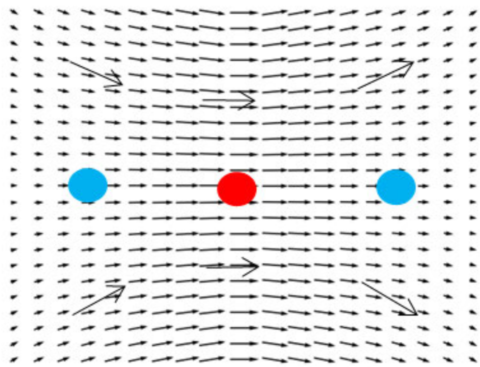
The main purpose of the experiment was to validate the basic sickness reduction effect of looking at the MSP/R during typical navigational content consumption, and furthermore assess its relative advantage, if any, to using the other popular rest frame object: the virtual nose. The experiment was run with two factors: the type of rest frame object containing - (1) None (Control condition), (2) Virtual nose, and (3) MSP/R; the type of the test content featuring (1) Space navigation and (2) Ship riding (see Fig. 4). The Space navigation had movements in 5 motion degrees of freedom, while as for the Ship riding, the rotation (roll, pitch and yaw, although coupled with slow forward motion) was much more pronounced (no pure side-way translation in either contents). Figures 1 and 4 illustrate the two test contents, and Fig. 5, the characteristics of the navigation profile in terms of the lateral and angular velocities along the navigation course.



(a) Pure side way motion



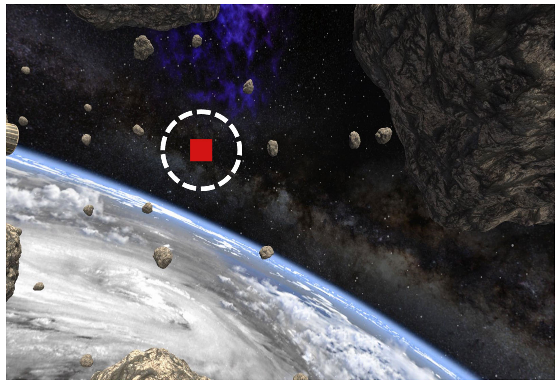
(b) Roll rotation



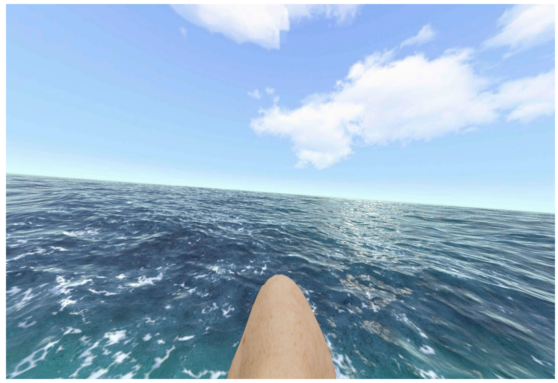
(c) Yaw rotation

FIGURE 3. Locating the MSP for motions without radial optical flow pattern (without forward/backward motion). Red dots indicate the locations obtained with blind intersection of the infinitely extended optical flow field, and blue, where the algorithm will actually place the MSP with additional analysis: for side-way motion (left), roll rotation (middle), yaw rotation (right).

The subject was asked to simply experience the fixed navigation ride contents and report their experiences with regard to the level of sickness and the sense of presence and immersion. Therefore, in summary, the experiment was designed as a 3 × 2 within-subject single measure (6 test conditions). The single measure (only one trial per condition) was applied to prevent any learning or habituation effect. We hypothesized not only of the significant VR sickness reduction effect of MSP/R, but also the less intrusion into the content and less degrading of the navigational experience (e.g. presence and immersion) as compared to the case of using the Virtual nose.



(a) Motion Singularity Point(MSP)



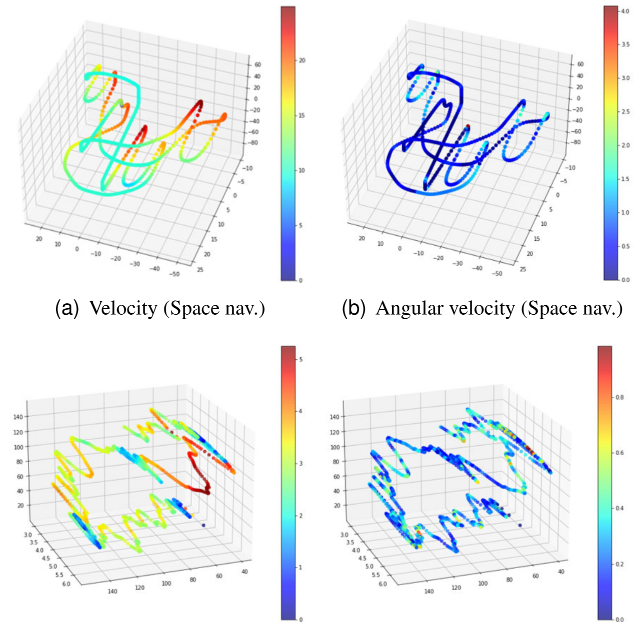
(b) Virtual nose

FIGURE 4. The Motion Singularity Point (MSP) in a virtual space exploration (left) and virtual nose in a virtual ship ride (right). MSP is estimated as the average radial center of the directional optical flow of the given image frame.

B. EXPERIMENTAL SET-UP AND PROCEDURE

More than 33 potential subjects were recruited through a closed university online community. The subjects filled out a self-reporting survey about their basic demographic backgrounds (including the extent of any prior VR experience) and tendency/sensitivity toward motion and simulator sickness (3 USD compensation). We used the reduced version of the MSSQ [31] for the latter. Potential subjects who indicated very high or low sensitivity (>75 or <25 percentile) to the self-reported VR sickness were excluded from the experiment. We opted for such a subject pool (rather than e.g., the groups in the extreme - highly sensitive or insensitive) in order to assess for any significant effect to an average user. In addition those with color amblyopia or color blindness were excluded. A final total of 30 participants (14 male and 16 female between the ages of 19 and 33, mean = 24.2 / SD = 3.56) participated in the actual experiment. 27 of them indicated prior experiences of using VR systems.

Those final subjects were paid 16 USD for their participation. All the subjects wound up completing the tasks despite being allowed to freely give up the experiment at any stage. Due to the pandemic, all equipment were sanitized after each treatment. They first filled out the consent agreement form, were briefed about the purpose of the experiment,



(a) Velocity (Space nav.) (b) Angular velocity (Space nav.)

(c) Velocity (Ship ride) (d) Angular velocity (Ship ride)

FIGURE 5. The characteristics of the navigation profiles in terms of the lateral and angular velocities for the Space navigation and Ship riding contents.

and explained of the experimental task. The subject sat on a chair (to avoid falling or losing balance due to possible sickness) and the administrator helped to correctly adjust the headset and calibrate the eye tracking sensor. We used the HTC Vive Pro Eye headset which is equipped with an eye tracking sensor to measure the time the subject viewed the MSP/R (indicated with the red dot) or the Virtual nose and investigate of any particular viewing pattern. The eye tracking data would provide us with a more accurate viewing pattern of the subjects instead of estimating it the head direction, especially because both the MSP/R and the virtual nose are typically not too far from the foveal region. The subject experienced the six different conditions in a balanced Latin square order. For each condition, the subject simply viewed the virtual space as automatically navigating the fixed path through the virtual space. The subject was free to look around and change one's viewpoint rather than fixating on the rest frame object (MSP/R or virtual nose). Such a method was adopted to observe and take into account of the natural user behavior of managing and handling of the sickness symptoms in each condition.

Before each test treatment, the subjects filled out the Simulation Sickness Questionnaire [32] to measure the baseline (before state) data. To measure the VR sickness online in association to the navigational course (at least in a limited way), a simple hand-held button to indicate moments (by a simple press) at which he/she felt a severe level of sickness was implemented. The subject was allowed to stop and discontinue the experiment for any reason, including the unbearable level of sickness. Between treatment trials, the subject rested at least 10 min and until reaching a sickness level considered negligible and safe before continuing on to the next treatment. For this, the SSQ score of below 30 and one's consent was needed, otherwise, the subject continued to rest. The experiment lasted up to 2 hours per subject (30 40 minutes per each treatment including rest and information gathering). The score of 30 (as an indicator or no or minimal sickness) was decided based on the average initial SSQ score of the subjects before starting the experiment (before state). Note that according to [32] the score of 20 was empirically deemed as such a level for 75 percentile population.

After each treatment, the subjects, as they rested, filled out the SSQ again to record the after-effects. The subcategory scores were scaled by the weight factors, as indicated in [32] for proper comparison. The level of user-perceived presence/immersion was also measured as an indicator of the VR user experience [33], using the modified SUS presence questionnaire [34] and the Igroup presence questionnaire (IPQ) [35]. The appendix includes the actual survey questions. After experiencing all treatments, some additional questions were asked (preferences, self-reported degradation in presence/immersion) and post briefings were taken. All survey questions were answered on a seven-point Likert scale. Finally, to assess the potential distraction factor, we asked the users to report if they remembered any particular objects from the first content they viewed (which were pre-designated and planted beforehand) without telling them about it ahead of time. The experiment was approved by the Institutional Review Board. There were 8 (set by the short term memory capacity [36]) different such objects - astronaut, alien, moon, yellow machine gun, container box, satellite, dish antenna, space shuttle. The test environment and contents were implemented using the version 2020.3.23 of Unity [37] running on a PC with the AMD Ryzen 7 5800X CPU, 32 GB RAM, Nvidia 3070 GPU.

V. EXPERIMENTAL RESULTS

A. SIMULATOR SICKNESS

2×3 way ANOVA with the Fisher's least significant difference (LSD) was used to analyze the collected sickness data. Fig. 6 shows the after sickness level as assessed by the SSQ for the six preset test conditions. Table 1 shows the pair-wise comparison and the associated statistical figures in detail (just for the conditions with statistically significant differences). Compared to the Control condition (None), the MSP/R brought about statistically significant reductions in the category of Nausea (p-value=0.0334). The statistically significant differences were seen in the Control-MSP/R and Virtual nose-MSP/R for the Space navigation, and in the Virtual nose-MSP/R for the Ship ride.

The type of motion (emphasized rotation) in ship riding is generally unfamiliar to the common user, and this, together with vection, was expected to cause even more severe sickness (or sea sickness). However, at the same time, the MSP also coincided mostly with some point on the ocean horizon (near the "calm" ocean surface). Sea sickness is also

TABLE 1. Pair-wise comparison of the SSQ data among the six test conditions (* and ** marks indicate statistically significant differences with p<0.05 and p<0.01 respectively).

	Space navigation			Ship ride		
	Control MSP/R	Control Virtual nose	MSP/R Virtual nose	Control MSP/R	Control Virtual nose	MSP/R Virtual nose
Nausea	0.004**	0.61	0.003**	0.09	0.52	0.05*

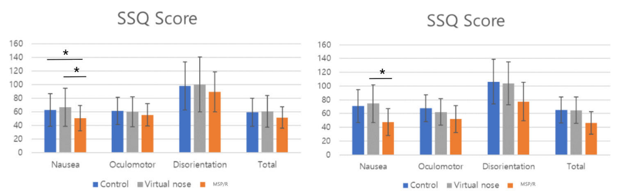


FIGURE 6. The comparison of the SSQ scores (after) among the Control, Virtual nose, and the Motion Singularity Point/Region (MSP/R) for the two test environments (95% confidence level).

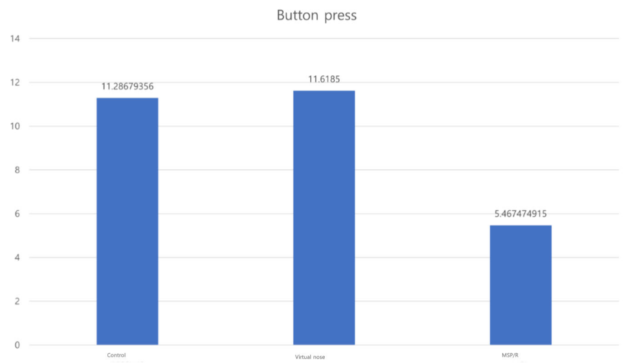


FIGURE 7. Sickness button press data (number of times) over the Space navigation course for the three tested conditions. Less Sickness presses were observed for the case of Motion Singularity Point/Region (MSP/R) overall.

known to come from the mismatch between the ship motion and the seemingly (not actually) "calm" ocean [38]. In the post briefing, subjects stated that they were actually even less familiar with the Space navigation and this content included almost all motion degrees of freedom. In this special case of Ship ride, therefore, we postulate that the sickness reduction effect of the MSP/R was weakened.

Interestingly the Virtual nose did not exhibit the expected sickness reduction effect in contrast to what has been reported in the research community [4], [6]. In fact, several subjects reported of even relatively more sickness in the Virtual nose condition. Note that in our experiment, we did not force the subject to look at either the virtual nose or the MSP/R, but to do so only freely.

The "Sickness" button data and eye tracking data as depicted in Fig. 7 and 8 confirm our assessment. Despite the sickness being felt over most of the navigational course, the attention of the subjects was still distributed over various places in the image space. Only little portion was concentrated to the Virtual nose, explaining the limited

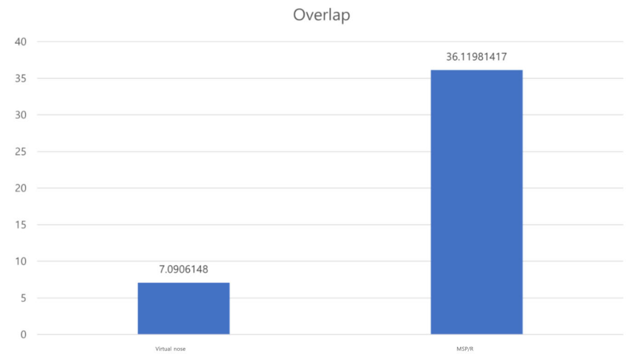


FIGURE 8. The extent of overlap (in number of frames) between the rest frame objects (Virtual nose and MSP/R) with the direction of the viewpoint for Space navigation in terms of the time the user's gaze stayed on the respective rest frame object. Much more overlap with the MSP/R than Virtual nose was observed as illustrated.

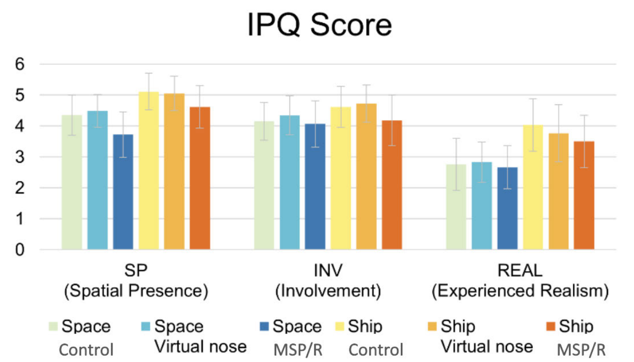


FIGURE 9. The comparison of the IPQ scores (after) between the default and with the Motion Singularity Point, Virtual nose for the two test environments.

sickness reduction effect in the actual usage. Fig. 8 illustrates how much the attention overlapped with either the Virtual nose or the MSP/R in terms of the time the user's gaze stayed on the respective rest frame object. In the case of MSP/R, it is clear that there was a much higher overlap (regardless of whether it was intentional or coincidental). The appendix includes the detailed data of sickness button and overlap time.

B. PRESENCE

We administered two presence/immersion questionnaires - the SUS and the IPQ. In both Fig. 9 and 10, the data and their analysis show no particular differences in the presence or immersion in different subcategories among the six conditions.

TABLE 2. Object recall test results as an indicator of the distraction factor. The default Control and MSP/R conditions show much higher score than the Virtual nose.

	astronaut	alien	moon	cannon	container	satellite	antenna	space ship	Avg
Control	21	30	15	15	3	6	0	3	93
MSP/R	27	24	21	9	3	6	9	3	102
Virtual nose	24	27	15	0	0	6	0	3	75

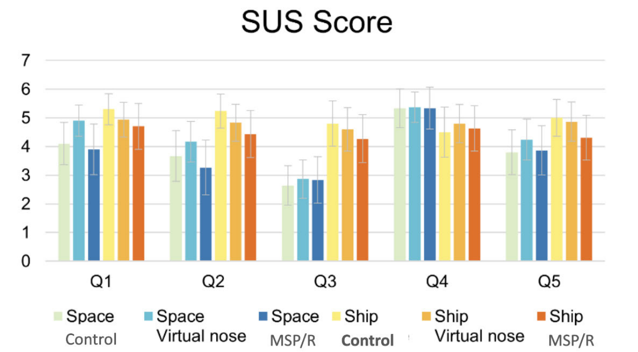


FIGURE 10. The comparison of the SUS scores (after) between the default and with the Motion Singularity Point, Virtual nose for the two test environments.

To assess the level of possible distraction, we administered an object recall task. Table 2 tabulates the results - high scores were obtained with the default (None) and MSP/R conditions with a statistical significance (see Table 2 for detailed statistical figures). Thus, as the eye tracking data also shows, looking at the MSP/R was more effective in reducing the sickness in actual usage, because aside from its role as the rest frame object, there is a higher probability of it coinciding with where the subject likes to attend to and thereby causing less distraction from the main content and less degrading of the immersive experience.

VI. SUPPLEMENT EXPERIMENT

In order to further confirm the claimed sickness reduction effect of the MSP/R, we separately compared the use of MSP/R to its opposite, a region with the largest motion information (MOF, most optical flow). We hypothesized that looking over to this region will cause the sickness to become worse. The supplement experiment was conducted for two types of apparent motion (forward and forward + rotation) presented as moving white dot patterns (in black background) eliciting the corresponding vection (see Fig. 11). The computation of the MOF was done in the similar way as computing the MSP, looking for the region with the most total optical flow magnitude.

The MOF would be the average position of the features within the found region. The image space was divided into 10 × 10 grid over which the search for MOF was conducted. Since there may be several candidates for the MOF (with a similar level of motion information), one was chosen randomly. The heat map in Fig. 11 illustrates the extent of the motion in the image for the two types of motion. For instance,

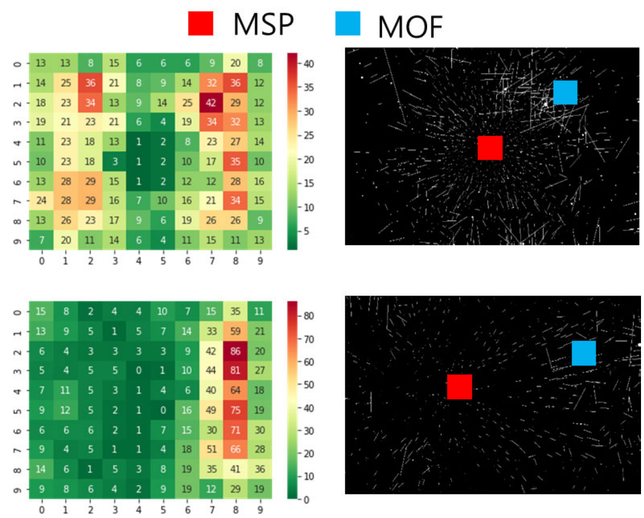
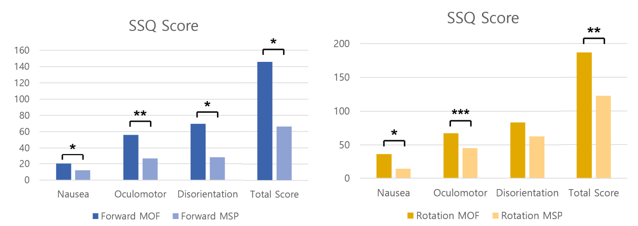


FIGURE 11. The distribution of the motion information (e.g. total optical flow magnitude) in the image space for two types of user motion - pure forward and forward with yaw rotation. Illustrated in the right are the actual moving dot pattern visual motion as presented to the user and the corresponding locations of the MSP and MOF.



(a) Forward (b) Forward + Rotation

FIGURE 12. The comparison of the SSQ scores (before and after) between the Most Optical Flow and the Motion Singularity Point for the two test environments.

we can readily see that for forward motion, the MSP is in the middle of the visual field, while the MOF is in the far periphery.

The subject was asked to either fixate and look at the MSP or MOF, and the before and after levels in the sickness were measured similarly. Eight subjects participated in this supplement experiment (5 males and 3 females between the ages of 21 and 35, mean = 25.8 / SD = 4.72) and the procedure was mostly similar to the other experiment. We omit the rest of the experimental details.

Fig. 12 shows the results and in all sickness categories and total score, the MSP consistently shows, again, of its sickness reduction effect (while otherwise for MOF) with the

TABLE 3. Seven questions in the modified/reduced IGroup Presence Questionnaire (IPQ).

Space Presence (SP)	Q1	Somehow I felt that the virtual world surrounded me.	1 (fully disagree) ~7 (fully agree)
	Q2	I felt like I was just perceiving pictures.	1 (fully disagree) ~7 (fully agree)
	Q3	I felt present in the virtual space.	1 (did not feel) ~7 (felt present)
Involvement (INV)	Q4	I was not aware of my real environment.	1 (fully disagree) ~7 (fully agree)
	Q5	I still paid attention to the real environment.	1 (fully disagree) ~7 (fully agree)
	Q6	I was completely captivated by the virtual world.	1 (fully disagree) ~7 (fully agree)
Experienced Realism (REAL)	Q7	The virtual world seemed more realistic than the real world.	1 (fully disagree) ~7 (fully agree)

TABLE 4. Five questions in the modified/reduced Slater-Usoh-Steed Presence Questionnaire (SUS).

Q1	I had a sense of "being there" in the virtual environment	1 (Not at all) ~7 (Very much)
Q2	There were times during the experience when the virtual environment was the reality for me...	1 (At no time) ~7 (Almost all the time)
Q3	The virtual environment seems to me to be more like...	1 (Image that I saw) ~7 (Somewhere that I visited)
Q4	I had a stronger sense of...	1 (Being elsewhere) ~7 (Being in the virtual environment)
Q5	During the experience I often thought that I was really standing in the virtual environment...	1 (Not very often) ~7 (Very much so)

statistical significance for both types of motion (Forward: p-value - N: 0.016, O: 0.0034, D: 0.023, TS: 0.010; Forward + Rotation: p-value - N: 0.014, O: 0.000002, D: 0.07, TS: 0.0035).

VII. LIMITATIONS AND DISCUSSION

Despite the positive result of validating the sickness reducing effect of the MSP/R, there are several limitations and possible extensions to our work. First, the MSP finding algorithm needs improvement to be more robust and general to cover all types of user motion. Motion analysis in the 3D space (vs. the current 2D optical flow based) is another consideration which can also alleviate the problem in the case the content image happens to contain much feature-less regions. Another limitation is the inability of such approach to handle independently moving objects within the scene, which produces optical flow but not due to user motion. Depending on the content flow, the location of the MSP can be erratic (due to sudden directional change) and jittery (due to noise or inaccurate optical flow estimation). Employing filtering techniques can partially alleviate the problem.

It has been reported previously that the use of the virtual nose went mostly unnoticed [4], [6]. Such a result requires further investigation because the experimental condition regarding how the user was instructed to utilize the virtual nose is unclear. Like any rest frame object, extended attention to it is expected to bring about the sickness reduction effect. It is quite plausible that the nose being unnoticed could be due to it being part of our body, and not noticing it consciously may be a separate issue from actual distraction from the main content. Thus the use of virtual nose could have produced greater sickness reduction if fixated longer, as much as that by the MSP/R. The point is that the MSP/R naturally overlaps with where the user is likely to look and it occludes much less of the original content. While, in our work, the MSP/R indication showed no significant influence to the user felt sense of presence and immersion, it should be noted that the test content was non-interactive (fixed navigation). For interactive contents, even a small dot can be of a nuisance and distraction and could cause performance degradation. Therefore MSP/R may be indicated only during the intermittently occurring interactive navigation.

One other interesting future work is to compare the use of MSP/R to (or even combine with) the two other popular methods of VR sickness reduction - namely, dynamic adjustment of field of view [10] and peripheral image blurring [11]. These two notable works limit the motion information to visual periphery, while our work induces the user to direct one's attention to the region of least motion information. Thus, they can be combined in a complementary manner e.g. such that the clear field of view is centered around the MSP and the ensuing periphery is blurred or blacked out. Finally, further validation is still needed, e.g. testing the proposed approach with a variety of VR contents, and including e.g. interactive navigation and 360 degree videos.

VIII. CONCLUSION

In this paper, we have proposed the Motion Singularity Point/Region (MSP/R) as an alternative rest frame for which fixation on it can potentially relieve the VR sickness during navigation. The validation experiment has shown promising results, clearly indicating sickness reduction effect of the MSP/R in comparison to the Virtual nose, especially due to its significant coincidence with the user perspective. In addition, the MSP, visualized as a small "dot" is much less content infringing than the virtual nose (typically 8~12 of the screen space and about 1800 times the small dot).

APPENDIX

A. MODIFIED/REDUCED IGROUP PRESENCE QUESTIONNAIRE (IPQ)

See Table 3.

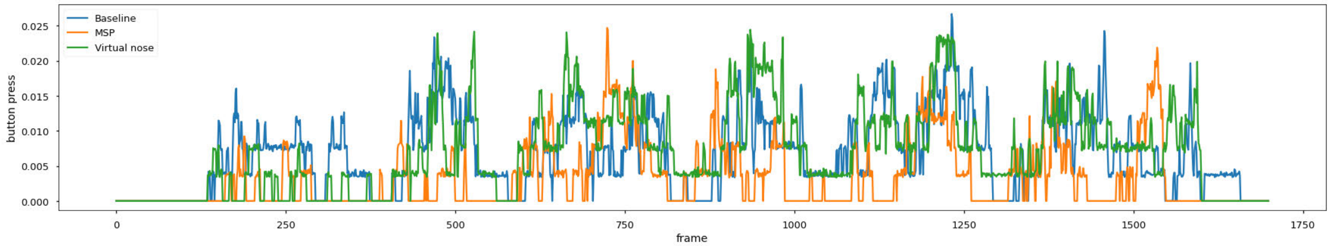


FIGURE 13. Sickness button press data over the Space navigation course for the three tested conditions. Less Sickness presses are observed for the case of Motion Singularity Point/Region (MSP/R) overall.

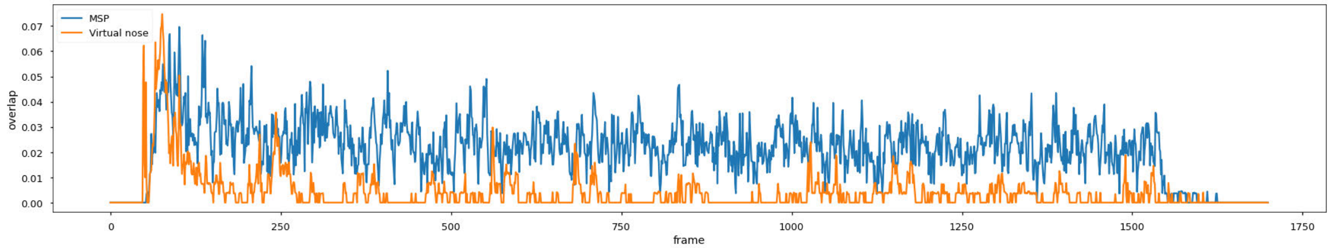


FIGURE 14. The extent of overlap between the rest frame objects (Virtual nose and MSP/R) with the direction of the viewpoint for Space navigation in terms of the time the user's gaze stayed on the respective rest frame object. Much more overlap with the MSP/R than Virtual nose was observed as illustrated.

B. MODIFIED/REDUCED SLATER-USOH-STEED QUESTIONNAIRE (SUS)

See Table 4.

C. SICKNESS BUTTON PRESS DATA

See Fig. 13.

D. EYE TRACKING OVERLAP DATA

See Fig. 14.

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MU-HYEON PARK received the B.S. degree in weapon system engineering from the Naval Academy of Korea, in 2016, and the M.S. degree in computer science and engineering from Korea University, Seoul, Republic of Korea. His research interests include augmented/virtual reality and human–computer interaction.

KWAN YUN received the B.S. degree in computer engineering from Korea University, Republic of Korea, in 2019. He is currently pursuing the M.S. degree in computer science and engineering with KAIST, South Korea. His research interests include computer graphics, augmented/virtual reality, and human–computer interaction.

GERARD J. KIM received the B.S. degree in electrical and computer engineering from Carnegie Mellon University, in 1987, and the M.S. and Ph.D. degrees in computer science from the University of Southern California, in 1994. He is currently a Professor of computer science and engineering with Korea University. His research interests include human–computer interaction, virtual/mixed reality, and computer music.