On the Computation of User Placements for Virtual Formation Adjustments during Group Navigation

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Abstract

Several group navigation techniques enable a single navigator to control travel for all group members simultaneously in social virtual reality. A key aspect of this process is the ability to rearrange the group into a new formation to facilitate the joint observation of the scene or to avoid obstacles on the way. However, the question of how users should be distributed within the new formation to create an intuitive transition that minimizes disruptions of ongoing social activities is currently not explored. In this paper, we begin to close this gap by introducing four user placement strategies based on mathematical considerations, discussing their benefits and drawbacks, and sketching further novel ideas to approach this topic from different angles in future work. Our work, therefore, contributes to the overarching goal of making group interactions in social virtual reality more intuitive and comfortable for the involved users.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Interaction design—Interaction design theory, concepts and paradigms;

1 Introduction

Navigating from one location to another while staying together as a group is a fundamental task of user interaction in social virtual reality [26]. To assist with this process, prior research has presented group navigation techniques that enable a dedicated navigator to control the movements of the entire group similar to a vehicle in the real world. To prevent collisions with objects and to optimize user placements during this process, a central idea behind these techniques is the ability to change the spatial layout of the group, e.g., by reducing its spatial extent to fit through narrow pathways or to rearrange users completely into a new formation that is beneficial for mutual interactions [14, 25, 28]. However, the integration of these *virtual formation adjustments*, as they were called in prior work [25, 28], is particularly challenging for teleportation-based group navigation techniques. Since discontinuous transitions were already shown to have a high risk of disrupting the users' spatial awareness (e.g., [3, 12, 18]), adjusting the users' spatial relation to their group members as part of the same process might introduce an additional source of disorientation that potentially disturbs ongoing interactions or discussions.

In a continuing attempt to reduce this risk, this paper takes a closer look at the process of discontinuous virtual formation adjustments from an arbitrary group formation before the teleport to a specific target formation after the teleport. Even though altering the spatial layout of the group deliberately directs the focus of the group to a new joint activity in the virtual environment, we believe that the order of users within the target formation plays an essential role in how intuitive the overall group transition is perceived. As a result, we present initial ideas on the development of algorithms that investigate spatial relationships in the original formation to determine a suitable user arrangement within the target formation. We discuss the advantages and disadvantages of our ideas and present an outlook of potential future research directions in this field.

The question of what constitutes an intuitive group transition is situated at the intersection of influences from visual computer science, mathematical optimization, and social anthropology. It might be dependent on the size of the group, its social composition, the individual expectations and preferences of its members as well as the use case within which group navigation is employed. Our work is, therefore, explicitly not motivated by the desire to derive a single perfect algorithm but to present initial ideas that demonstrate the versatility of this topic and give impulses for future research. The contributions of this work can be summarized as follows:

- The introduction of four strategies to compute user arrangements within the target formation based on the spatial relationships in the original formation
- A discussion of exemplary group transitions produced by these strategies to demonstrate their characteristic behaviors
- The provision of a source code project for the Unity game engine that enables others to experiment with the proposed rearrangement strategies in self-created examples [27]
- An overview of further conceptual approaches for computing user rearrangements to inspire future work

While a full-scale empirical user study to validate the perceptual effects of different formation transitions is still subject to future work, our work provides promising initial insights into the design space of improving virtual formation adjustments for group navigation.

2 Related Work

Social virtual reality systems simulate interactions between people by representing them as avatars in a shared virtual environment, the movements of which are dictated by the real-time tracking data of the involved head-mounted displays and controllers [16]. While this definition does not exclude the physical collocation of the individual users [26], a major benefit of social VR lies in the connection of geographically separate people when a real-world encounter is not feasible or desired. As a result, social VR systems have already been used for realizing a wide range of both professional (e.g., [1, 30]) as well as personal gatherings (e.g., [8, 31]) over long distances. While still not identical to real-world experiences, researchers have found indications that social VR can elicit a range of emotional states [17] as well as behavioral patterns [21, 29] that were also observed in the real world. Overall, the combination of these familiar interactions with the additional supernatural activities that virtual environments can offer has the potential to satisfy a wide range of social, experiential, self-related, and functional needs of users [22].

As hardware performance continues to increase, virtual environments can extend over large areas that can only be explored by virtual locomotion. Therefore, a group may form at one place in the

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Figure 1: Virtual formation adjustments enable the navigator to change the group's spatial formation as part of the group navigation process. In this example, the navigator (yellow) plans a teleport that reshapes the group into a circle formation for observing an object.

environment before deciding to relocate to a new site together to continue their discussions, for example, as part of a joint tour [14, 28]. To accomplish this task, the system may rely on coordinated individual navigation efforts by the users (Section 2.1) or provide them with a dedicated group navigation technique (Section 2.2). A specific teleportation-based group navigation technique provides the main motivation of the work presented in this paper (Section 2.3).

2.1 Coordinated Individual Navigation

The most straightforward solution for getting somewhere together in social VR is to agree on a meeting point and have each user navigate there individually using a common single-user travel technique like steering or teleportation [4]. To prevent users from getting lost during this process, wayfinding helpers like arrows [5, 15, 24], traces [9, 15, 24], maps [5, 20], and World-in-Miniatures [2, 6] may be provided. The alternative is to follow the movements of an experienced user of the group, which can, however, be challenging when teleportation is used as the main travel method. Therefore, researchers have proposed different effects to visually enhance an instantaneous user transition for observers [7, 10, 23] and confirmed that seeing a teleporting user's selection ray and target is an essential cue for observers as well [19].

2.2 Group Navigation Techniques

A prominent alternative to following an experienced user by individual navigation is the use of dedicated group navigation techniques that allow the experienced user to control travel for all group members simultaneously [26]. Exemplary prototypes of this concept have been demonstrated in the form of joint steering in front of a projection screen [14] as well as joint teleportation of geographically distributed users with head-mounted displays [25, 28]. Group navigation techniques can be categorized by their employed mechanisms for users to come together (Forming), decide on navigational responsibilities (Norming), perform the actual travel (Performing), and split up again (Adjourning) [25]. Given the additional efforts resulting from managing travel for the entire group, Performing techniques are typically most involved as they have to communicate ongoing navigation actions in a comprehensible way, assist the group with avoiding collisions with objects in the environment, and support placing the group in a meaningful spatial arrangement for the joint observation and discussion of content [28]. The latter two requirements can be approached with *virtual formation adjustments*, allowing the navigator or the system to alter the arrangement of users relative to each other as part of the navigation process [25, 28].

2.3 Formation-Changing Group Teleportation

Weissker and Froehlich introduced a teleportation-based group navigation technique to facilitate joint guided museum tours for five to ten geographically distributed users [28]. This technique enabled the navigator to plan different types of group teleportations, which included the mere translation of the group in its current formation, the rotation of the group in its current formation, the uniform scaling of distances between all group members, and the complete rearrangement of group members into a new formation. The technique offered functional formations like circles and half-circles (cf. [13]) as well as a compact grid and queue formation for traversing narrow pathways, all of which were shown to be beneficial for conducting guided group tours. The arrangement of users within the target formation was based on fixed equidistant positions, with users being assigned to these positions based on a simple heuristic that only considered each user's identification number for sorting. Figure 1 shows an exemplary scenario in which the navigator rearranges the group in a circle formation to discuss a common object of interest together. Our work in this paper will present initial ideas that incorporate information from the original formation into the computation of the target formation to reduce social disruptions during these transitions.

3 Initial Strategies for Rearranging User Groups into New Formations

We present four initial strategies on how group navigation techniques can arrange users along a desired target shape based on the spatial relationships in the original formation. We begin by introducing a more general formal definition of the problem (Section 3.1) before presenting two constraints that we applied for our approaches of this paper to restrict the vast solution space (Section 3.2). Based on the idea of having fixed slots that users will be assigned to after the transition, we then present and discuss three mathematical functions to evaluate distortions introduced by a particular user rearrangement (Section 3.3) as well as one solution approach that alters previously selected user-slot assignments to represent the original formation more closely (Section 3.4).

3.1 Problem Statement

We consider a set of users U with $|U| = n > 1$ that represents the members of a social group operating a group navigation technique to move through the virtual environment together. The spatial-orientational arrangement of these users in the environment at a certain point in time is referred to as the group's *formation* [13], which can be mathematically represented by the set of all users' position vectors $\{\mathbf{p_0}, \mathbf{p_1}, ..., \mathbf{p_{n-1}}\}, \mathbf{p_i} \in \mathbb{R}^3$ and quaternions $\{\mathbf{q_0}, \mathbf{q_1}, ..., \mathbf{q_{n-1}}\}, \mathbf{q_i} \in \mathbb{H}$ encoding their viewing orientations.

For group navigation techniques that enable the specification of changes to the group's formation for improved collaboration, it is often more convenient to select the desired shape of the new formation based on the intended purpose rather than providing an exact list of new positions and orientations for each user separately. For example, if the intention is to look at an exhibit together, a circle or half-circle formation with all users oriented towards the center is beneficial. If the intention is to traverse narrow pathways, a compact grid or queue formation with all users facing forward could be selected. Based on this input, the task of the group navigation technique is to suggest a set of updated user positions $\{\mathbf{p'_0}, \mathbf{p'_1}, ..., \mathbf{p'_{n-1}}\}, \mathbf{p'_i} \in \mathbb{R}^3$ that are all located on the selected shape, with orientations $\{\mathbf{q'_0}, \mathbf{q'_1}, ..., \mathbf{q'_{n-1}}\}, \mathbf{q'_i} \in \mathbb{H}$ matching the intention of that shape. For simplicity in writing, we will use the term *target formation* to refer to the shape across which users will be distributed after the transition, with the task of the group navigation technique to find a suitable *user arrangement within the target formation*. Figure 2 presents an exemplary graphical depiction of this problem, in which the navigator of a six-user group uses the technique of Weissker and Froehlich [28] to transition into a circle formation.

While the computation of any position on a mathematically defined shape, as well as of suitable orientations associated with each position, is straightforward, the main research challenge emerging

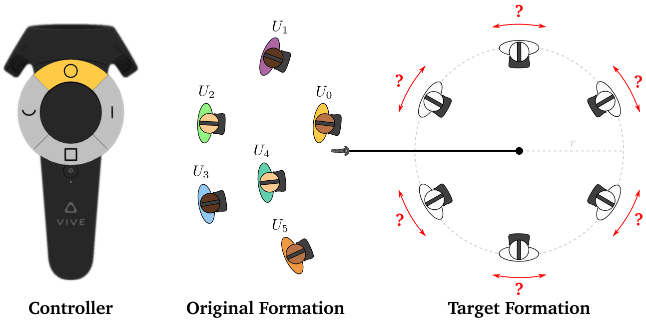

Figure 2: A group is in an arbitrary spatial formation when the navigator plans a group teleport involving a virtual formation adjustment to a target formation. Here, the circle formation is selected as an example. We investigate basic algorithms for arranging users within the target formation in an attempt to make the transition feel intuitive based on the spatial relationships in the original formation.

from this task is the question of which user should go where on the selected shape such that the overall transition is perceived as more intuitive compared to a fixed or random placement of users. We argue that the most suitable arrangement of users within the target formation minimizes the amount of distortions it introduces to the spatial relationships in the original user formation. To formalize this idea, we suggest looking at all possible combinations of two users $U_i, U_j \in U$ with $U_i = (\mathbf{p_i}, \mathbf{q_i})$ and computing a function D that quantifies the difference between the respective positions and/or orientations. The overall error of a certain user arrangement within the target formation can then be computed by summing up the absolute changes it introduces to D for all user pairs U_i, U_j with $i \neq j$:

$$E = \sum_{i=0}^{n-1} \sum_{j=0}^{n-1} |\, D(U_i, U_j) - D(U_i', U_j') \,| \tag{1}$$

If the selected function D is symmetric, i.e., $D(U_i, U_j) = D(U_j, U_i)$, the summations can be simplified such that each user pair is only considered once. In this case, the index j starts at $i+1$ instead of 0.

3.2 Restriction of the Problem Space

Two major challenges that arise from the above-described problem statement are the infinitely large space of potential user arrangements within the target formation as well as the large number of potential factors that can be considered to compute the function D. Our work presented in this paper, therefore, makes two simplifying assumptions to reduce the potential solution space.

Discrete Positions on Target Shape Our four presented approaches all begin by considering only a subset of the solution space in which users are evenly distributed within the target formation. As a result, the target formation is divided into a set of n slots that users will be assigned to after the transition. Using this constraint, the problem statement reduces to finding a bijective mapping that assigns each unique user to a unique slot. While our first three presented approaches iterate over all $n!$ possible user assignments assuming an equidistant distribution of slots and simply output the one resulting in the lowest error E (Section 3.3), our fourth approach allows for the slight adjustment of those initial slot positions once an assignment of users has been determined to resemble the corresponding user distances in the original formation more closely (Section 3.4).

Reduction to 2D Calculations Given that several beneficial formations presented in related work on social anthropology are defined based on their 2D projection onto the ground plane (e.g., circles, half-circles, queues), our approaches presented in this paper also restrict themselves to a 2D projection of users and their viewing directions. As a result, the representation of a user's position and orientation can be simplified to a two-dimensional vector $\mathbf{p_i} \in \mathbb{R}^2$ and a one-dimensional viewing angle $q_i \in \mathbb{R}$, respectively. Without loss of generality, our approaches assume a coordinate system in which the y-axis is pointing upwards, with positions on the ground plane being represented by x and z coordinates.

3.3 Smallest Difference of a User-Slot Mapping

Our suggested strategies to compute differences between formations are based on Euclidean distances (Section 3.3.1), angular distances (Section 3.3.2), and a weighted combination of both components (Section 3.3.3). The benefits and drawbacks of each strategy will be discussed in Section 3.3.4 using three exemplary group transitions.

3.3.1 Difference Function Based on Euclidean Distances

Our first suggestion is based on the idea that transitions into a new formation could be perceived as more intuitive if local neighborhoods in the original formation are preserved as well as possible. As a result, user pairs that are close together in the original formation should ideally arrive in neighboring slots of the target formation to be able to continue interactions with each other if desired.

To realize this idea, we propose the function D_e that reflects the Euclidean distance between user positions projected on the ground plane, which is based on a function $\tilde{D}_e$ with an additional normalization stage. If the projected position $\mathbf{p_i} \in \mathbb{R}^2$ of a user $U_i \in U$ consists of the two components $\mathbf{p_i} = (x_i, z_i)$, the function is defined as follows:

$$\tilde{D}_e(U_i, U_j) = \sqrt{(x_i - x_j)^2 + (z_i - z_j)^2} \tag{2}$$

However, using $\tilde{D}_e$ in this form does not lead to error scores E that are invariant to the scale of the target formation, meaning that the selected slot assignment changes for different sizes of the same target formation. This is due to the function $\tilde{D}_e$ yielding lower error scores when the absolute distance between user pairs is represented as closely as possible. However, given that the target formation might have a different size than the original formation, we suggest an additional normalization stage of the computed $\tilde{D}_e$ values on a per-user level to emphasize the importance of local neighborhoods over exact absolute distances.

After analyzing all values of $\tilde{D}_e$ for a specific user $U_i \in U$, this normalization stage sets $D_e(U_i, U_a) = 0$ for the user $U_a \neq U_i$ that has the smallest score, $D_e(U_i, U_b) = 1$ for the user $U_b \neq U_i$ that has the largest score, and linearly interpolated values between 0 and 1 for the remaining users $U_j \neq U_i$. After this additional step, the resulting function is not symmetric anymore since, for example, U_b could be the closest user from the perspective of U_a (i.e., $D_e(U_a, U_b) = 0$) while another user U_c further away from U_a but directly behind U_b is closest from the perspective of U_b (i.e., $D_e(U_b, U_a) > 0$).

3.3.2 Difference Function Based on Angular Distances

Our second suggestion is based on the idea that transitions into a new formation could be perceived as more intuitive if angular relationships between users in the original formation are preserved as well as possible. As a result, a user who is currently in a certain part of another user's field-of-view should ideally arrive in a slot that is located in the same part of the field-of-view for visual consistency.

To realize this idea, we propose the function D_a that reflects the horizontal angle at which another user is located relative to the reference user's current viewing direction, which is based on a function $\tilde{D}_a$ with an additional normalization stage. For this, the orientation angle $q_i \in \mathbb{R}$ of a user $U_i \in U$ is converted into a direction vector $\mathbf{v} = (v_1, v_2)$ by rotating the default forward direction by q_i. The function $\tilde{D}_a(U_i, U_j)$ between two users $U_i, U_j \in U$ can then be defined as the signed angle from U_i's forward direction $\mathbf{v}$ to the

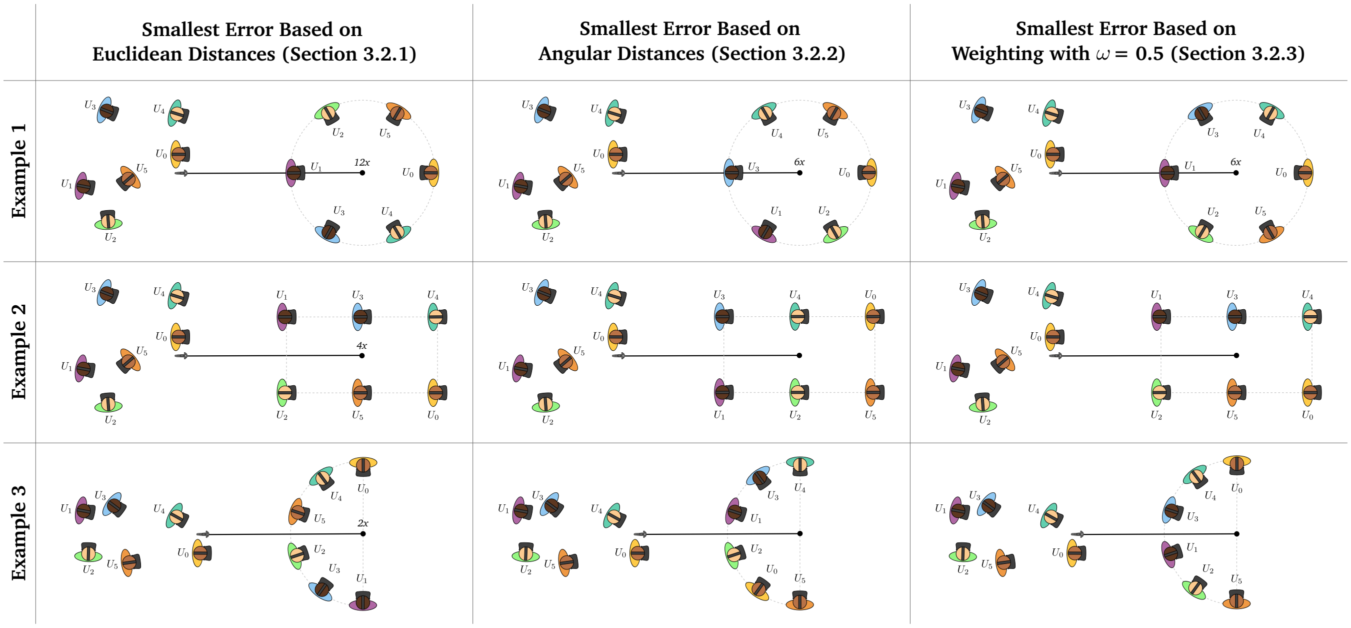

Figure 3: Three examples demonstrating the results of our arrangement strategies based on fixed slot positions as presented in Section 3.3. Each row demonstrates the results of the three presented strategies for the same transition from a particular user formation (left in each cell) to a target formation defined by its shape (right in each cell). A number above the center point of the target formation indicates how many rotated or mirrored variants of the shown arrangement with the same error are present.

difference vector $\mathbf{w} = \mathbf{p_j} - \mathbf{p_i} = (w_1, w_2)$ pointing from the position of U_i to the position of U_j:

$$\tilde{D}_a(U_i, U_j) = atan2(w_2 \cdot v_1 - w_1 \cdot v_2, w_1 \cdot v_1 + w_2 \cdot v_2) \tag{3}$$

This function is not symmetric, i.e., $\tilde{D}_a(U_i, U_j) \neq \tilde{D}_a(U_j, U_i)$, as one user U_i could directly look at another user U_j while U_j does not necessarily have to look back. While normalization of this function as described for D_e does not provide immediate benefits due to the already restricted angular range from $-180°$ to $180°$, it might nonetheless be desirable if D_a is used as part of a combination with other difference criteria. Therefore, we suggest dividing $\tilde{D}_a$ by $180°$ to compute the value of D_a in the reduced range of $[-1; +1]$ for improved comparability. When taking the difference between two values of D_a as part of the computation of E, we always consider the shortest of the two possible circular paths.

3.3.3 Weighted Error Combinations

Our third suggestion is based on the idea that a combination of both distance- and angular-based influences could be beneficial to unify the advantages of both components.

To realize this idea, we propose computing two total errors for a particular slot mapping with Equation 1, one based on D_e (referred to as E_e) and one based on D_a (referred to as E_a). The final error E for a user-slot mapping is then defined as a weighted linear combination of E_e and E_a based on a weighting factor $\omega \in [0, 1]$:

$$E = \omega \cdot E_e + (1 - \omega) \cdot E_a \tag{4}$$

Using this expression, the choice of larger values for ω increases the influence of E_e while smaller values of ω favor E_a instead. By choosing $\omega = 0.5$, both error terms have equal contributions.

3.3.4 Evaluation and Discussion

Figure 3 shows the output of our three presented error minimization strategies based on Euclidean distances (left), angular distances (center), and an equally weighted combination of both terms (right) for three exemplary transitions. Each transition involves a group of six users led by U_0 as the navigator, who selects a different target formation to be transitioned to in each example. Details on the computation of the equidistant slot positions can be found in the accompanying source code project. While these examples were selected to demonstrate the individual nuances of each approach, our three strategies are not limited to this particular group size or the chosen target formations.

Example 1: Transition to a Circle Formation The first example depicts a situation in which the group arrived at a specific location in the virtual environment and formed three subgroups for individual discussions and activities. Users $\{U_1, U_2, U_5\}$ formed a circle for a conversation, U_3 is an independent observer, and $\{U_0, U_4\}$ stand side by side and see an interesting exhibit in the distance when U_0 decides to rejoin the subgroups into a unified circle formation around this exhibit. Employing the Euclidean distance-based error E_e as a selection criterion for the target formation keeps the initial clusters by assigning the corresponding users to neighboring slots. Given the symmetric arrangement of slots in the target formation, there is a total of twelve user-slot assignments with the same smallest error, which are the six rotated variants of the arrangement shown in the figure in both clockwise and counter-clockwise order. The angular distance-based error E_a tears the clusters apart in favor of an improved placement of users in each other's field of view. As U_1 is rotated more towards U_5 than U_2 in the original formation, U_1 looks directly at U_5 in the target formation while U_2 is placed directly to the right of U_1 as before. The spatial relationship of U_4 being left of U_0 is broken apart in favor of having both users in the correct part of U_3's field of view. There are only six concurrent user-slot assignments with the same error E_a as the available directional information results in different scores for the clockwise and counter-clockwise variants of the same user order. This characteristic is also present for the equally weighted error E_w, which in this example selects six of the twelve candidate arrangements produced by E_e.

Example 2: Transition to a Grid Formation The second example depicts a similar situation as before, but this time, U_0 sees a narrow pathway ahead that the group has to fit through. Therefore, they decide to transition the group to a grid formation. Once again, the Euclidean distance-based error function E_e keeps the clusters of the original formation by assigning the involved users to neighboring slots. In particular, U_1, U_2, and U_5 are placed along a corner of the grid while U_0 and U_4 assume neighboring positions at the other end of the formation. The symmetries in the grid formation result in four arrangements with the same smallest error, which are created by all combinations of (i) mirroring the arrangement shown in the figure around the center point of the formation and (ii) swapping its top and bottom rows. The angular distance-based error function E_a selects a single best arrangement in which the two clusters of interacting users $\{U_0, U_4\}$ and $\{U_1, U_2, U_5\}$ are lined up in the top and bottom row, respectively. The equally weighted error E_w selects one of the four candidate arrangements produced by E_e.

Example 3: Transition to a Half-Circle Formation Coming out of a narrow pathway, the third example depicts a situation in which users have slightly moved away from the previous grid formation by physical locomotion. Seeing a wall with a painting ahead, U_0 decides to transition the group to a half-circle formation. In contrast to the previous two examples, the spatial relationships in the original formation are more ambiguous regarding potential interactions within the group. U_0 and U_4 might interact with each other based on their closeness although U_4 is outside of U_0's field of view. The remaining users form a close cluster at the back of the formation, where U_1, U_2, and U_3 could be part of a conversation with U_3's focus shifting towards the navigator U_0. The Euclidean distance-based error function E_e once again assigns users of the two clusters to neighboring slots, thereby producing two equivalent best user arrangements given by the clockwise or counter-clockwise order of the same result. The angular distance-based function E_a provides a single best arrangement that dissolves the neighborhood of U_4 and U_0 and disconnects U_5 from the larger cluster of remaining users. The equally weighted error E_w produces a new arrangement in which the two clusters are kept together, with the larger cluster being arranged to resemble the angular relationships of the original formation more closely. The placement of U_4 to the right of U_0, however, introduces an inconsistency with the original formation.

Discussion The three presented strategies use different heuristics to arrange users within the selected target formation in an attempt to resemble characteristic spatial properties present in the original formation. While we believe that either approach provides benefits over a fixed assignment of users to slots based on their identification number as done in prior work [28], the decision in favor of one strategy or another seems to depend more on the use case, personal preferences, and individual expectations. The Euclidean distance-based function E_e emphasizes the preservation of user clusters in close proximity to each other, but it ignores how users are oriented towards each other within each cluster and, therefore, does not take advantage of removing users from a cluster who happen to be close even though their attention is focused on somebody else. The angular distance-based function E_a, on the other hand, scatters conversing users across target formations with differently oriented slots, which minimizes directional inconsistencies and therefore likely reduces moments of disorientation before being able to continue mutual interactions. However, as user distances are not considered, multiple conversing subgroups are likely to have overlapping conversation spaces after transitions into circular formations. The equally weighted error function appears to combine the advantages of both previous approaches in many cases, but it can still result in unexpected arrangements of individual user pairs if such an inconsistency minimizes the global error introduced by the transition. Depending on the target formation, all approaches have the potential to yield multiple user arrangements with the same lowest error by exploiting symmetries. In these cases, additional heuristics could be employed to select the final arrangement that is used for the transition.

3.4 Three-Step Approach with Adjusted Slot Positions

While the subdivision of the target formation into slots with equidistant neighborhoods is a helpful algorithmic simplification that allows for an exhaustive evaluation of rearrangements, we believe that it could be beneficial for social interactions if the spatial proximity of users in the original formation is not only reflected by neighborhoods in the target formation. Therefore, once a candidate user-slot mapping has been identified, we suggest adjusting the distance of neighboring slots to resemble the corresponding user distances in the original formation. To realize this idea, we experimented with several concurrent alternatives and arrived at the following three-step algorithm that combines approaches presented from the previous section and extends them to output non-equally distributed user arrangements across the target formation:

1. Use the Euclidean distance-based error metric E_e to identify the best $x \geq 1$ user-slot assignments.
2. For each of the x mappings, adjust the distances between neighboring slots within the target formation based on how far the assigned users are apart in the original formation (see Section 3.4.1).
3. Considering the adjusted positions from the previous step, select the user arrangement(s) with the smallest angular distance-based error E_a.

Given that details on the functions E_e (Step 1) and E_a (Step 3) were already provided earlier, the following section provides additional information on the computation of adjusted slot positions based on a previously selected user-slot assignment.

3.4.1 Slot Adjustments

Given an assignment of users to slots in the target formation, the calculation of adjusted slot positions based on the distances between users in the original formation varies for different geometric shapes. Without loss of generality, we will provide exemplary calculation details for a few common target formations.

Straight Line The two slot positions at the endpoints of the line remain unchanged. The remaining slots are shifted along the line to proportionally represent the original Euclidean distances of the assigned users. To realize this, the original distances d_{ij} of all user pairs $U_i, U_j \in U$ that were assigned as neighbors in the line formation are summed up to a total score S, and the slot positions in the line formation are shifted such that their distance to each other represents the percentage of d_{ij}/S.

Cirlce and Half-Circle For the circle, one arbitrary slot position remains unchanged and serves as a reference. For the half-circle, the two slot positions at the endpoints remain unchanged. The remaining slots are distributed along the circular arc to proportionally represent the original Euclidean distances of the assigned users. To realize this, the original distances d_{ij} of all user pairs $U_i, U_j \in U$ that were assigned as neighbors in the target formation are summed up to a total score S, and the slot positions in the target formation are shifted such that their angular offsets represent the percentage of d_{ij}/S.

Grid Grid formations offer multiple options as to which constraints to apply to the adjustment of slots. For our grid with three rows and two columns as shown in Figure 4, we keep all corner slot positions unchanged and only adjust the position of two slots in between such that both columns individually represent the original Euclidean distances of their assigned users. To realize this, the original distances d_{ij} between neighboring user pairs $U_i, U_j \in U$ that were assigned to a column are summed up to a total score S for each

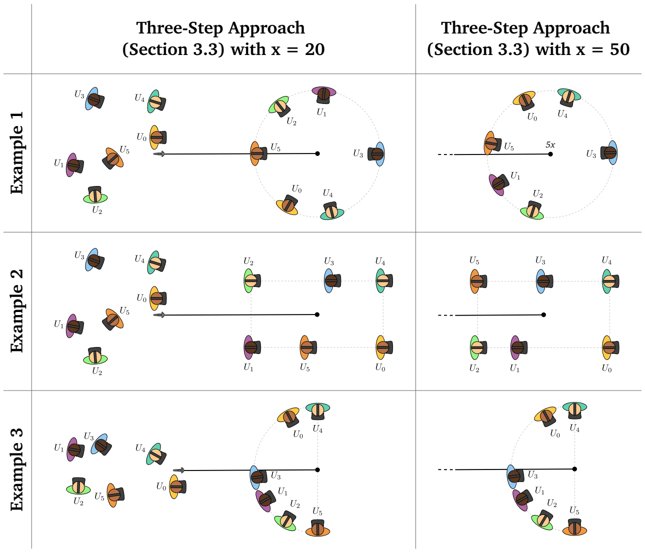

Figure 4: Results of our three-step algorithm presented in Section 3.4 with $x = 20$ and $x = 50$ using the same scenarios as in Figure 3.

column separately, and the center slot position is shifted such that its distances to the corner slot in front of and behind it represent the corresponding percentages. The distance between the two columns is fixed to achieve a more regular visual appearance of the formation.

3.4.2 Evaluation and Discussion

The parameter x of our described three-step algorithm indirectly controls the influence of the E_e and E_a on the overall result. A larger value of x results in fewer solution candidates that are discarded based on E_e in the first step, which increases the influence of E_a. If $x = n!$, slot positions are adjusted for every potential solution and only E_a is considered for selecting the result.

Figure 4 shows the output of the three-step algorithm in the same exemplary situations as discussed before, using $x = 20$ and $x = 50$ as examples. After the individual slot adjustments, the circle and half-circle formations clearly represent the spatial clusters of the original formations. While the increase from $x = 20$ to $x = 50$ does not yield a difference in the half-circle example, it does introduce a difference to the circle formation in that a slightly different user order within the two spatial clusters is selected. Clusters are also kept together in the grid formation, but their closeness is less pronounced when spanning across both columns based on our constraint of having a fixed column distance. Future enhancements of this approach could, therefore, experiment with interpolated slot positions between columns if the resulting less-structured group shape is acceptable within the usage context of the group navigation technique. The increase from $x = 20$ to $x = 50$ in the grid example only introduces a change to the order of the three users $\{U_1, U_2, U_5\}$ that faced each other before the transition.

Overall, the proposed three-step strategy appears to be beneficial when a mere representation of spatial clusters by direct neighborhoods is not sufficient for the usage context. The adjustment of slot positions based on the assigned users provides clearer gaps to visibly separate user clusters from each other in the target formation as well, which could be beneficial to maintain existing social ties and interactions across the group navigation process. On the other hand, larger gaps within the target formation might also tear users apart more than necessary, which could also be detrimental when the group navigation process intends to introduce a deliberate focus shift onto a new joint activity.

4 Limitations and Future Directions

Our algorithms and functions presented in this paper provide initial ideas for the computation of favorable user placements within the target formation based on the spatial relationships present in the original formation. While the first results provided by these algorithms in our hypothetical scenarios appear promising, the underlying inference of complex social relationships and interactions purely based on spatial information of the original formation is a challenging process that is prone to misinterpretations in real situations. This limitation could be partially addressed by sensing and including additional components from proxemics [11] in the presented formulas, but individual user expectations of what constitutes a meaningful and intuitive group transition might still vary. Therefore, future work involves the conduction of behavioral user studies in which user groups are tasked to rearrange themselves into different formations in real-world scenarios. This could allow us to derive rules about what is considered a good or meaningful transition. Personal preferences or specific roles within a group might also be an essential factor in the proposed weighting functions that could allow for more fine-grained control. In addition to interpersonal factors, it could also be relevant to minimize the absolute changes introduced to a user's viewing direction to minimize sickness symptoms during steering or to prevent spatial disorientation during teleportation.

From an algorithmic point of view, testing the entire solution space exhaustively to determine the global optimum concerning an error metric is not scalable to larger user groups. Therefore, future approaches might consider incremental optimization approaches that start with a certain arrangement of users within the target formation and apply changes (e.g., by swapping neighborhoods or adjusting interpersonal distances) until a local optimum is reached. Very large groups might also be divided into subgroups, allowing for hierarchical optimizations to limit the calculation time. Further developments could also involve the application of geometric shape morphing algorithms to transition the convex hull of user positions in the original formation to match the desired target formation. Graph layouting algorithms like force-directed graph drawing could be harnessed, with the additional constraint that the final layout has to be limited to the geometric shape of the target formation. While this work restricted formations to the 2D space, numerous new challenges and questions arise when dealing with groups occupying a three-dimensional domain. As a result, a more rigorous analysis of the applicability of our proposed strategies or how they might have to be altered is an essential component of future work.

5 Conclusion

The computation of meaningful user arrangements when transitioning to a new formation as part of the group navigation process is a challenging task that is influenced by both mathematical as well as human factors. Our approaches provide clear improvements over the naïve and fixed user arrangement pursued in previous work, but they also demonstrate that the impression of a best or most intuitive group transition can depend on the usage context as well as individual preferences. We briefly outlined the benefits and drawbacks of our approaches based on a few examples and would like to encourage the community to experiment with our accompanying Unity project to gain further insights into the algorithms using self-created examples [27]. While user studies on our approaches are still subject to future work, we hope that our ideas inspire novel discussions on the design space of virtual formation adjustments in an attempt to make group transitions more intuitive for the involved users.

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