RIGIDITY AND PERSISTENCE FOR ENSURING SHAPE MAINTENANCE OF MULTI-AGENT META-FORMATIONS

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ABSTRACT

This paper treats the problem of merging formations, where the underlying model of a formation is graphical. We first analyze the rigidity and persistence of meta-formations, which are formations obtained by connecting several rigid or persistent formations. Persistence is a generalization to directed graphs of the undirected notion of rigidity. In the context of moving autonomous agent formations, persistence characterizes the efficacy of a directed structure of unilateral distance constraints seeking to preserve a formation shape. We derive then, for agents evolving in a two- or three-dimensional space, the conditions under which a set of persistent formations can be merged into a persistent meta-formation, and give the minimal number of interconnections needed for such a merging. We also give conditions for a meta-formation obtained by merging several persistent formations to be persistent.

Key Words: Formations, meta-formations, rigidity, persistence, autonomous agents.

I. INTRODUCTION

Recently, significant interest has been shown in the behavior of autonomous agent formations (groups of autonomous agents interacting with each other) [1–5], and more recently on meta-formations, which is the name ascribed to an interconnection of formations, generally with the individual formations being separate [6, 7]. In this paper, autonomous agent means any human-controlled or unmanned vehicle moving by itself and having a local intelligence or computing capacity, such as ground robots, air vehicles or underwater vehicles. Many reasons, such as obstacle avoidance and dealing with a predator, can lead a (meta-) formation to be split into smaller formations which are later remerged. Those smaller formations need to be organized in such a way that they can behave autonomously when the formation is split. Conversely, some formations may need to be temporarily merged into a meta-formation to accomplish a certain task, this meta-formation being split afterwards.

The particular property of formations and meta-formations which we analyze here is persistence. This graph-theoretical notion which generalizes the notion
of rigidity to directed graphs was introduced in [5] to analyze the behavior of autonomous agent formations governed by unilateral distance constraints. Many applications require the shape of a multi-agent formation to be preserved during a continuous move. For example, target localization by a group of unmanned airborne vehicles (UAVs), using either angle of arrival data or time difference of arrival information, appears to be best achieved (in the sense of minimizing localization error) when the UAVs are located at the vertices of a regular polygon [8]. Other examples of optimal placements for groups of moving sensors can be found in [9]. This objective can be achieved by explicitly keeping some inter-agent distances constant. In other words, some inter-agent distances are explicitly maintained constant so that all the inter-agent distances remain constant. The information structure arising from such a system can be efficiently modelled by a graph, where agents are abstracted by vertices and actively constrained inter-agent distances by edges.

We assume here that those constraints are unilateral, i.e., that the responsibility for maintaining a distance is not shared by the two concerned agents but relies on only one of them. This unilateral character can be a consequence of the technological limitations of the agents. Some UAVs can for example not efficiently sense objects that are behind them or have an angular sensing range smaller than 360° [10–12]. Also, some of the authors of this paper are working with agents in which optical sensors have blind three dimensional cones. It can also be desired to ease the trajectory control of the formation, as it allows so-called leader-follower formations [1, 13, 14]. In such a formation, one agent (leader) is free of inter-agent constraints and is only constrained by the desired trajectory of the formation, and a second agent (first follower) is responsible for only one distance constraint and can set the formation relative orientation. The other agents have no decision power and are forced by their distance constraints to follow the two first agents.

This asymmetry is modelled using directed edges in the graph. Intuitively, an information structure is persistent if, provided that each agent is trying to satisfy all the distance constraints for which it is responsible, it can do so, with all the inter-agent distances then remaining constant, and as a result the formation shape is preserved. A necessary but not sufficient condition for persistence is rigidity [5], which intuitively means that, provided that all the prescribed distance constraints are satisfied during a continuous displacement, all the inter-agent distances remain constant (these concepts of persistence and rigidity are more formally reviewed in the next section). The above notion of rigidity can also be applied to structural frameworks where the vertices correspond to joints and the edges to bars. The main difference between rigidity and persistence is that rigidity assumes all the constraints to be satisfied, as if they were enforced by an external agency or through some mechanical properties, while persistence considers each constraint to be the responsibility of a single agent. As explained in [5], persistence implies rigidity, but it also implies that the responsibilities imposed on each agent are not inconsistent, for there can indeed be situations where this is so, and they must be avoided. Rigidity is thus an undirected notion (not depending on the edge directions), while persistence is a directed one. Both rigidity and persistence can be analyzed from a graph-theoretical point of view, and it can be proved that if a formation is rigid (resp. persistent), then almost all formations represented by the same graph are rigid (resp. persistent) [5, 15, 16].

As stated in [6], the problem of merging rigid formations into a rigid meta-formation has been considered in a number of places. In [17, 18], the rigidity of a multi-graph (a graph in which some vertices are abstractions of smaller graphs) is analyzed. In two dimensions the vertices of a multigraph can be thought of as two dimensional solid bodies at the boundary of which some bars can be attached; two vertices are then connected by an edge if the corresponding bodies are attached to the same bar. Of course, the idea extends obviously to three dimensions. Operational ways to merge two rigid formations into a larger rigid formation can also be found in [3, 19].

In this paper, we treat the problem of determining whether a given meta-formation obtained by merging several persistent formations is persistent. For this purpose, we first consider the above mentioned problem of determining whether a meta-formation obtained by merging rigid formations is rigid. We also analyze the conditions under which a collection of persistent formations can be merged into a persistent meta-formation. Conditions are then given on the minimal number of additional links that are needed to achieve such a merging. Note that throughout the paper, we always assume that the internal structure of the formations cannot be modified. Moreover, we use a convenient graph-theoretical formalism, abstracting agents by vertices and (unilateral) distance constraints by (directed) edges.

After reviewing some properties of rigidity and persistence of graphs in Section II, we examine in Section III the issues mentioned above for agents evolving in a two-dimensional space. We show in Section IV how our results can be generalized in a three-dimensional space, and explain why this generalization can only partially be achieved. Note that some proofs are omitted.
for three-dimensional space when they are direct generalization of results in two-dimensional space. The paper ends with the concluding remarks in Section V. Some preliminary results published in [20] without proofs are included here at a greater level of details. Moreover, Propositions 7 and 8 correct the unproven Proposition 5 in [20], which did not take the case described in Proposition 7 into account.

II. REVIEW OF RIGIDITY AND PERSISTENCE

2.1 Rigidity

As explained in Section I, the rigidity of a graph has the following intuitive meaning: suppose that each vertex represents an agent in a formation, and each edge represents an inter-agent distance constraint enforced by an external observer. The graph is rigid if for almost every such structure, the only possible continuous moves are those which preserve every inter-agent distance, as shown in Fig. 1a and b. For a more formal definition, the reader is referred to [5, 15]. In $\mathbb{R}^2$, that is, if the agents represented by the vertices of the graph evolve in two dimensions, there exists a combinatorial criterion to check if a given graph is rigid:

**Theorem 1.** (Laman [21, 22]) A graph $G = (V, E)$, with $|V| > 1$, is rigid in $\mathbb{R}^2$ if and only if there is a sub-set $E' \subseteq E$ such that

(i) $|E'| = 2|V| - 3$,

(ii) for all non-empty $E'' \subseteq E'$ there holds

$$|E''| \leq 2|V(E'')| - 3,$$

where $V(E'')$ is the set of vertices incident to edges of $E''$.

Unfortunately, the analogous criterion in $\mathbb{R}^3$ is only necessary.

![Fig. 1](image-url)  

**Theorem 2.** If a graph $G = (V, E)$, with $|V| > 2$, is rigid in $\mathbb{R}^3$, there exists $E' \subseteq E$ such that

(i) $|E'| = 3|V| - 6$,

(ii) for all non-empty $E'' \subseteq E'$, there holds $|E''| \leq 3|V(E'')| - 6$, where $V(E'')$ is the set of vertices incident to edges of $E''$,

(iii) the graph $G'(V, E')$ is 3-connected (i.e., remains connected after removal of any pair of vertices).

Condition (iii), which also implies the 3-connectivity of $G$, is not usually stated but is independently necessary even if the two first conditions are satisfied. Fig. 1c shows for example a non-rigid graph for which (i) and (ii) are satisfied, but not (iii). Intuitively, the graph $G'$ in the theorem needs to be sufficient to ensure “alone” the rigidity of $G$. 3-connectivity is then needed as otherwise two or more parts of the graph could rotate around the axis defined by any pair of vertices whose removal would disconnect the graph. Note that such connectivity condition is not necessary in two-dimensional spaces, as the counting conditions (i) and (ii) of Theorem 1 imply the 2-connectivity. For more information on necessary conditions for rigidity in three-dimensional spaces, we refer the reader to [23].

We say that a graph is *minimally rigid* if it is rigid and if no single edge can be removed without losing rigidity. It follows from the results above that a graph is minimally rigid in $\mathbb{R}^2$ (resp. in $\mathbb{R}^3$) if and only if it is rigid and contains $2|V| - 3$ (resp. $3|V| - 6$) edges [15]. Therefore we have the following characterization of minimal rigidity in $\mathbb{R}^2$.

**Theorem 3.** (Laman [21, 22]) A graph $G = (V, E)$, with $|V| > 1$, is minimally rigid in $\mathbb{R}^2$ if and only if it is rigid and contains $2|V| - 3$ edges, or equivalently if and only if

(i) $|E| = 2|V| - 3$,

(ii) for all non-empty $E'' \subseteq E$ there holds $|E''| \leq 2|V(E'')| - 3$, where $V(E'')$ is the set of vertices incident to edges of $E''$.

2.2 Persistence

Consider now that the constraints are not enforced by an external entity, but that each constraint is the responsibility of one agent to enforce. To each agent, one assigns a (possibly empty) set of unilateral distance constraints represented by directed edges: the notation $(i, j)$ for a directed edge connotes that the agent $i$ has to maintain a constant distance to $j$ during any continuous move. As explained in the Introduction, the persistence of the directed graph means that each agent is trying to satisfy its constraints, the distance between any pair of connected or non-connected agents
is kept constant during any continuous move, and as a consequence the shape of the formation is preserved. Note, though, that the assignments given to an agent may be impossible to fulfill, in which case persistence is not achieved. An example of a persistent and a non-persistent graph having the same underlying undirected graph is shown in Fig. 2. For a more formal definition persistence is applicable in three and larger dimensions, it is not sufficient to imply the desired stability of the formation shape. For the shape stability, the graph corresponding to a three-dimensional formation needs in addition to be \textit{structurally persistent}. In $\mathfrak{H}^3$, a graph is structurally persistent if and only if it is persistent and contains at most one leader, \textit{i.e.}, at most one vertex with no outgoing edge. In $\mathfrak{H}^2$, persistence and structural persistence are equivalent. Similar to minimal rigidity, we say that a graph is \textit{minimally persistent} if it is persistent and if no single edge can be removed without losing persistence. It is proven in [5, 16] that a graph is minimally persistent if and only if it is persistent and minimally rigid. The number of edges of such a graph is thus uniquely determined by its number of vertices as it is the case for minimally rigid graphs.

\textbf{III. RIGIDITY AND PERSISTENCE OF 2D META-FORMATIONS}

\textbf{3.1 Rigidity}

Consider a set $N$ of disjoint rigid (in $\mathfrak{H}^2$) graphs $G_1, \ldots, G_{|N|}$ having at least two vertices each, and a set $S$ of single-vertex graphs $G_{|N|+1}, \ldots, G_{|N|+|S|}$. Those graphs are called \textit{meta-vertices}, and it is assumed that no modification can be made on their internal structure: no internal edge or vertex can be added to or removed from a meta-vertex. We define the merged graph $G$ by taking the union of all the meta-vertices and of some additional edges $E_M$, each of which has end-points belonging to different meta-vertices.

The conditions under which the merging of two meta-vertices leads to a rigid graph are detailed in [19]: if both meta-vertices contain more than one vertex, the merged graph is rigid if and only if $E_M$ contains at least three edges, the aggregate of which are incident to at least two vertices of each meta-vertex. This is actually a particular case of the following result for an arbitrary number of graphs (analogous to a result in [18] which is obtained under the assumption that no vertex of any meta-vertex is incident to more than one edge of $E_M$):

\textbf{Theorem 5.} If it contains at least two vertices, $G = (\bigcup_{N,S} G_i) \cup E_M$ (with $N$ and $S$ as defined at the beginning of this section) is rigid if and only if there
exists $E'_M \subseteq E_M$ such that

(i) $|E'_M| = 3|N| + 2|S| - 3,$

(ii) for all non-empty $E''_M \subseteq E'_M,$ there holds

$$|E''_M| \geq 3|I(E'_M)| + 2|J(E'_M)| - 3,$$

where $I(E'_M)$ is the set of meta-vertices such that there are at least two vertices within the meta-vertex incident to that are all edges of $E'_M,$ and $J(E'_M)$ is the set of meta-vertices such that there is precisely one vertex within the meta-vertex that is incident to one or several edges of $E''_M.$ Note that in each case, there can be an arbitrary number of vertices in the meta-vertex which are not incident on any edge of $E'_M.$

The proof of this theorem partly relies on the following lemma, proved in [25], and that we state here for both $\mathfrak{n}^2$ and $\mathfrak{n}^3,$ intending to use it in the next section.

**Lemma 1.** Let $G(V, E)$ be a rigid graph (in $\mathfrak{n}^2$ or $\mathfrak{n}^3$), and $G'_1, \ldots, G'_N$ be minimally rigid subgraphs of $G$ having distinct vertices. Then there exists a minimally rigid subgraph $G'(V, E')$ of $G$ containing all vertices of $G$ and all subgraphs $G_i.$

We can now prove Theorem 5.

**Proof.** For every $G_i,$ let $G'_i$ be a minimally rigid subgraph of $G_i$ on the same vertices (the existence of such subgraphs follows directly from the definition of minimal rigidity, and they can be obtained by successively removing edges from the initial graph). Since they are minimally rigid, they contain $2|V_i| - 3$ edges if $G_i \subseteq N$ and no edge if $G_i \subseteq S.$

We first suppose that there exists a set $E'_M$ as described in the theorem and prove the rigidity of $G,$ by proving the minimal rigidity of one of its subgraph viz., $G' = (V, E') = (\bigcup_{N, S} G'_i) \cup E'_M$ which contains all its vertices. The number of edges in $G'$ is

$$|E'| = |E'_M| + \sum_{G_i \in N} |E_i'| = 3|N| + 2|S| - 3 + \sum_{G_i \in N} (2|V_i| - 3) = 2|V| - 3,$$

since $|V| = |S| + \sum_{G_i \in N} |V_i|.$ To show that $G'$ satisfies the second condition of Theorem 1, suppose that there exists a subset of edges $E'' \subseteq E'_M$ such that $|E''| > 2|V(E'')| - 3,$ let $I$ be the set of meta-vertices containing at least two vertices of $V(E'')$ and $J$ the set of meta-vertices containing only one vertex of $V(E'').$ Let now $E''_M = E_M \cap E''$ and for each $i,$ $V''_i = V(E'') \cap V_i$ and $E''_i = E'' \cap E''_i.$ There holds $V(E'') = \sum_{G_i \in I} |V''_i| + |J|,$ and $E'' = E''_M + \sum_{G_i \in I} |E''_i|.$ Moreover, since each $G'_i$ is minimally rigid, it follows from Theorem 3 that $|E''_i| \geq 2|V_i| - 3.$ We have then

$$|E''_M| = |E''| - \sum_{G_i \in I} |E''_i| > 2|V''| - 3 - \sum_{G_i \in I} (2|V_i| - 3) = 3|I| + 2|J| - 3$$

so that this $E''_M \subseteq E'_M$ does not satisfy condition (ii) in the theorem.

We now suppose that $G$ is rigid. It follows from Lemma 1 that there is a minimally rigid subgraph $G'(V, E') \subseteq G$ containing all $G'_i.$ Let $E'_M = E' \cap E_M;$ we prove that $E'_M$ satisfies the condition of this theorem. Since $G'$ is minimally rigid, there holds $|E'| = 2|V| - 3.$ Moreover, we have $|E'| = |E'_M| + \sum_{i \in N} |E_i'|,$ and $|V| = \sum_{G_i \in N} |V_i| + |S|,$ so that

$$|E'_M| = 2|V| - 3 - \sum_{G_i \in N} (2|V_i| - 3) = 3|N| + 2|S| - 3.$$
algorithm that is used for rigid graphs (see [24], or even faster [18]).

For a given collection of meta-vertices, we say that $G$ is an edge-optimal rigid 
merging if it is obtained by merging $G_1$ and $G_2$ (a) but not if it is obtained by merging $G_1$, $G_2'$ and $G_3'$ (b). The dashed 
edges represent the edges of $E_M$.

Fig. 3. The graph represented in (a) and (b) is an edge-optimal rigid 
merge if it is obtained by merging $G_1$ and $G_2$ (a) but not if it is obtained by merging $G_1$, $G_2'$ and $G_3'$ (b). The dashed 
edges represent the edges of $E_M$.

3.2 Persistence

Next we analyze the case where the meta-vertices $G_i$ are directed persistent graphs, and adapt the defini-
tions of $N$ and $S$ in consequence. If it is possible to merge them into a persistent graph, then it is possible 
to do so in such a way that all the edges of $E_M$ leave vertices which have an out-degree not greater than two in $G$: a set of edges $E_M$ that would make $G$ persistent 
but that would not satisfy this property could indeed be 
reduced by Proposition 1 until it satisfies it. Moreover, we have the following proposition.

**Proposition 2.** Let $G = (\bigcup_{i \neq j} N_i G_i) \cup E_M$ with $N$ and $S$ as defined at the beginning of this section, and with all $G_i$ persistent. If no vertex left by an edge of $E_M$ 
has an out-degree larger than two, then $G$ is persistent 
if and only if it is rigid.

**Proof.** Rigidity is a necessary condition for persistence, 
so we just have to prove that it is here sufficient. Let $G'$ be a (directed) graph obtained from $G$ by removing 
edges leaving vertices with out-degree larger than two until no such vertex exists in the graph. It follows 
from Theorem 4 that we just need to prove the rigidity 
of any such $G'$. For every $i$, let $G_i'$ be the restriction 
of $G'$ to the meta-vertex $G_i$. Since in $G$, every edge of $E_M$ leaves a vertex with an out-degree at most two, 
there holds $G' = (\bigcup_{i \neq j} N_i G_i') \cup E_M$ as no edge of $E_M$ 
is removed when building $G'$. Moreover, for every $i$, $G_i'$ 
can be obtained from $G_i$ by removing edges leaving 
vertices with an out-degree larger than two until no such vertex exists in the graph anymore. The only 
vertices that are not left by exactly the same edges in $G$ 
as in $G_i$ are indeed those left by edges of $E_M$, which 
y by hypothesis have an out-degree at most two and are 
therefore unaffected by the edge-removal procedure. It 
follows then from the persistence of all $G_i$ and from 
Theorem 4 that all $G_i'$ are rigid. And since $G$ is rigid, 
$E_M$ satisfies the necessary and sufficient conditions of 
Theorem 5. Therefore, the graph $G' = (\bigcup_{i \neq j} N_i G_i') \cup E_M$ 
is also rigid, as the conditions of Theorem 5 do not depend 
on the edges inside the different meta-vertices. As 
explained above, this implies the persistence of $G'$.

The condition on the out-degrees of the vertices 
with an outgoing edge of $E_M$ can be conveniently re-
expressed in terms of degrees of freedom: to each DOF 
(within a single meta-vertex) of any vertex there corre-
sponds at most one outgoing edge of $E_M$. By an abuse 
of language, we say that such edges leave a vertex with one or more local DOF, i.e. a vertex which inside its 
meta-vertex has one or more DOF and which is then left 
by no more edges of $E_M$ than the number of DOF it
has. This allows reformulating Proposition 2, the proof of which can directly be extended to any dimension, in a dimension-free way:

**Theorem 7.** A collection of persistent meta-vertices can be merged into a persistent graph if and only if it can be merged into a persistent graph by adding edges leaving vertices with one or more local DOF; the number of added edges not exceeding the number of local DOF. In that case, the merged graph is persistent if and only if it is rigid.

If one or more edges of $E_M$ do leave a vertex with an out-degree larger than two, no criterion has been found yet to determine whether the merged graph is persistent or not, while also taking advantage of the fact that the graph is obtained by merging several persistent meta-vertices.

Combining Theorem 7 with what is known and reviewed above regarding the merging of two rigid meta-vertices, we conclude: two persistent meta-vertices $G_a$ and $G_b$ each having two or more vertices can be merged into a persistent graph if and only if three edges leaving vertices with local DOF can be added in such a way that they are incident to at least two vertices in each meta-vertex. There must thus be at least three local DOF available among the vertices in $G_a$ and $G_b$. Conversely, if there are available three local DOF among the vertices of $G_a$ and $G_b$, since no vertex can have more than two DOF, it is possible to add a total of at least three edges leaving at least two vertices of $G_a \cup G_b$. The vertices to which those edges arrive can then be chosen in such a way that at least two vertices of both $G_a$ and $G_b$ are incident to edges of $E_M$, as in the example shown in Fig. 4. It follows then from Theorem 5 that this graph is rigid, which by Theorem 7 implies that the merged graph is persistent:

**Proposition 3.** Two persistent meta-vertices each having two or more vertices can be merged into a persistent graph if and only if the sum of their DOF numbers is at least three. At least three edges are needed to perform this merging, and merging can always be done with exactly three edges.

If one or two of the meta-vertices are single vertex graphs, the result still holds, but the minimal number of added edges (and therefore the number of needed DOF) are then. We define the number of missing DOF ($m_{\text{DOF}}$) to be the maximal number of DOF that any graph with the same number of vertices can have, less the number of DOF the graph actually has. In $\mathbb{R}^2$, this maximal number is two for the single vertex graphs, and three for other persistent graphs. There is an interesting consequence: when the minimal number of edges is used to merge two meta-vertices $G_a$ and $G_b$, the number of missing DOF is preserved through the process, i.e. $m_{\text{DOF}}(G_a \cup G_b \cup E_M) = m_{\text{DOF}}(G_a) + m_{\text{DOF}}(G_b)$.

Consider now an arbitrary number of persistent meta-vertices, possibly containing single-vertex graphs, but such that the total number of vertices is at least two. If the sum of their number of missing DOF is no greater than three, it follows from Proposition 3 that any two of them can be merged in such a way that the obtained graph is persistent and that the total number of missing DOF remains unchanged. Any pair of those meta-vertices would indeed contain at least the required number of DOF. Doing this recursively, it is possible to merge all these meta-vertices into a single persistent graph. In case there are more than three missing DOF, the total DOF number is by definition smaller than $3|N| + 2|S| - 3$, which is the minimal number of edges required to make the merged graph rigid. It follows then from Theorem 7 that such meta-vertices cannot be merged in a persistent graph by addition of interconnecting edges. This proves the following result:

**Proposition 4.** A collection of persistent meta-vertices $N \cup S$ (with $N$ and $S$ as defined in the beginning of this section) can be merged into a persistent graph if and only if the total number of missing DOFs is no greater than three, or equivalently if the total number of local DOF in $N \cup S$ is at least $3|N| + 2|S| - 3$. At least $3|N| + 2|S| - 3$ edges are needed to perform this merging, and merging can always be done with exactly this number of edges.

As when merging rigid meta-vertices, we say that $G$ is an edge-optimal persistent merging if no single edge of $E_M$ can be removed without losing persistence. Again, if all meta-vertices are minimally persistent, then $G$ is an edge-optimal persistent merging if and only if it is minimally persistent.
Theorem 8. \( G = (\bigcup_{N,S} G_i) \cup E_M \) (with \( N \) and \( S \) as defined at the beginning of this section and with all \( G_i \) persistent) is an edge-optimal persistent merging if and only if it is an edge-optimal rigid merging and all edges of \( E_M \) leave vertices with local DOF.

Proof. Let \( G \) be a persistent merging. If there is an edge that lies in \( E_M \) leaving a vertex with no local DOF, then it follows from Proposition 1 that the graph obtained by removing this edge would also be persistent, and therefore persistence.

Now if \( G \) is a persistent merging for which all edges of \( E_M \) leave local DOF but which is not an edge-optimal rigid merging, then by removing one edge of \( E_M \) it is possible to obtain a rigid graph which by Proposition 2 is also persistent, so that \( G \) is not an edge-optimal persistent merging.

There remains to prove that an edge-optimal rigid merging \( G \) where all edges of \( E_M \) leave local DOF is an edge-optimal persistent merging. Since \( G \) is rigid, it follows from Proposition 2 that it is also persistent. Moreover, since it is an edge-optimal rigid merging, removing any edge of \( E_M \) destroys rigidity and therefore persistence.

Combining Theorems 8 and 6 leads to the following more explicit characterization of edge-optimal persistent merging.

Theorem 9. \( G = (\bigcup_{N,S} G_i) \cup E_M \) (with \( N \) and \( S \) as defined at the beginning of this section and with all \( G_i \) persistent) containing at least two vertices is an edge-optimal persistent merging in \( \mathcal{H}^2 \) if and only if the following conditions all hold:

(i) \( |E_M| = 3|N| + 2|S| - 3 \),

(ii) for all non-empty \( E''_M \subset E'_M \), there holds

\[ |E''_M| \leq 3I(E''_M) + 2J(E''_M) - 3 \]

with \( I(E''_M) \) and \( J(E''_M) \) as defined in Theorem 5.

(iii) all edges of \( E_M \) leave vertices with local DOF.

Note that an efficient way to obtain such a merging is provided in the discussion immediately preceding Proposition 4.

IV. RIGIDITY AND PERSISTENCE OF 3D META-FORMATIONS

4.1 Rigidity

We now consider a set \( N \) of disjoint rigid (in \( \mathcal{H}^3 \)) graphs \( G_1, \ldots, G_{|N|} \) having at least three vertices each, a set \( D \) of graphs containing two (connected) vertices \( G_{|N|+1}, \ldots, G_{|N|+|D|} \), and a set \( S \) of single-vertex graphs \( G_{|N|+|D|+1}, \ldots, G_{|N|+|D|+|S|} \). As in Section III, these graphs are called meta-vertices, and we define the merged graph \( G \) by taking the union of all the meta-vertices, and of some additional edges \( E_M \) each of which has end-points belonging to different meta-vertices.

The merging of two rigid meta-vertices, each containing more than two vertices, is treated in [19]: at least six edges are needed, and they must be incident to at least three vertices of each meta-vertex (which is necessary for 3-connectivity). But these conditions are only necessary, as they do not imply 3-connectivity. For example, the so-called “double-banana” graph in Fig. 1c can be obtained by merging two distinct rigid tetrahedral meta-vertices (1, 3, 4, 5) and (2, 5, 7, 8) using a total of six edges incident to four vertices of each meta-vertex. However, it is always possible to achieve a rigid merging using exactly six edges incident to exactly three vertices of each meta-vertex, with no single vertex having more than three incident edges out of the six. With a minor modification, the merging result above holds in the cases where at least one meta-vertex has less than three vertices: The required number of edges is different, as summarized in Table 1 where \( \min |E_M| \) represents the minimal number of edges required to merge the meta-vertices \( G_a(V_a, E_a) \) and \( G_b(V_b, E_b) \) into a rigid graph. Also, if a meta-vertex has less than three vertices, all of them should be incident to edges of \( E_M \), otherwise at least three of them should be. When merging several meta-vertices, there is no available necessary and sufficient condition for the rigidity of \( G \). Determining whether a merged graph is rigid in \( \mathcal{H}^3 \) is indeed a more general problem than determining whether a given graph is rigid (for which it suffices to take \( N = D = \emptyset \)) and there is no known set of combinatorial necessary and sufficient conditions for this. The next proposition implies however that the rigidity of the merged graph \( G \) only depends on \( E_M \), on the vertices to which nodes of \( E_M \) are incident and on the belonging of the \( G_i \) to \( N \), \( D \) or \( S \). Its proof, omitted here for space reasons, is available in [25].

Proposition 5. Let \( G = (\bigcup_{N,D,S} G_i) \cup E_M \) with \( N, D, S \) as defined at the beginning of this section. Suppose that a meta-vertex \( G_i \) is replaced by a meta vertex \( G'_i \) with the same set of vertices incident to \( E_M \), with the same set membership, \( N, S \) or \( D \), as \( G_i \), but otherwise with different internal structure. Let \( G' \) be the graph so obtained. Then \( G' \) is rigid if and only if \( G \) is rigid.
Moreover, we have the following necessary condition:

**Theorem 10.** Let $G_i$ for $i = 1, 2, \ldots, \left| N \right| + \left| D \right| + \left| S \right|$ be rigid meta-vertices, and suppose $G = (\bigcup_{N, D, S} G_i) \cup \bigcup_{M} E_M$ (with $N, D, S$ as defined at the beginning of this section) is rigid in $\mathbb{R}^3$ and contains at least three vertices. Then there exists $E_M' \subseteq E_M$ such that

(i) $|E_M'| = 6\left| N \right| + 5\left| D \right| + 3\left| S \right| - 6$,

(ii) for all non-empty $E_M'' \subseteq E_M'$, there holds

$$|E_M'| \leq 6|I(E_M')| + 5|J(E_M')| + 3|K(E_M')| - 6,$$

where $I(E_M')$ is the set of meta-vertices such that there are at least three vertices within the meta-vertex all incident to edges of $E_M'$, or precisely two vertices within the meta-vertex which are unconnected and both incident to edges of $E_M'$, $J(E_M')$ is the set of meta-vertices such that there are precisely two vertices within the meta-vertex which are connected and both incident to edges of $E_M'$, $K(E_M')$ is the set of meta-vertices such that there is precisely one vertex within the meta-vertex that is incident to one or several edges of $E_M'$. Note that in each case, there can be an arbitrary number of vertices in the meta-vertex which are not incident on any edge of $E_M'$.

Moreover, the graph $(\bigcup_{N, D, S} G_i) \cup E_M'$ is rigid.

**Proof.** For every $G_i$, let $G_i'$ be a minimally rigid subgraph of $G_i$ on the same vertices. As mentioned in its proof, Lemma 1 can also be applied in a three-dimensional space. So there is a minimally rigid subgraph $G'(V,E') \subseteq G$ containing all $G_i'$. Let $E_M' \subseteq E_M$ be connected and both incident to edges of $E_M'$, then it follows from several applications of Proposition 5 that $(\bigcup_{N, D, S} G_i) \cup E_M'$ is rigid. \hfill \Box

Table 1. Minimal number of edges required to merge two rigid graphs $G_a$ and $G_b$ into a single rigid graph in $\mathbb{R}^3$.

| $|V_a|$ | $|V_b|$ | $\min |E_M|$ |
|-------|-------|-------|
| 1     | 1     | 2     |
| 1     | 2     | 3     |
| 2     | 2     | 4     |
| 2     | 2     | 5     |
| 2     | 2     | 6     |

Note that the rigidity of $(\bigcup G_i) \cup E_M'$ is explicitly mentioned here and not in Theorem 5, because in a two-dimensional space it follows directly from sufficiency of the counting conditions. But, the counting conditions of Theorem 10 are not sufficient for rigidity, as the non-rigid graph of Fig. 1c which can be obtained by merging two rigid tetrahedral meta-vertices (1, 3, 4, 5) and (2, 6, 7, 8) would indeed satisfy. Nevertheless, one can deduce from Theorem 10 that $G$ is an edge-optimal rigid merging in $\mathbb{R}^3$ if and only if it is rigid and $|E_M'| = 6\left| N \right| + 5\left| D \right| + 3\left| S \right| - 6$, using $E_M'$ exactly in the same way as in Theorem 6.

4.2 Persistence

We consider now that all meta-vertices $G_i$ are persistent graphs, and adapt the definitions of $N, D$ and $S$ in consequence. Theorem 7 can be generalized to three dimensions, as it follows from Proposition 2, the proof of which can be immediately extended to three dimensions.

**Theorem 11.** A collection of (structurally) persistent meta-vertices can be merged into a (structurally) persistent graph if and only if it can be merged into a (structurally) persistent graph by adding edges leaving vertices with one or more local DOF. In that case, the merged graph is persistent if and only if it is rigid.

**Proof.** Suppose first that a collection of persistent meta-vertices can be merged into a persistent graph in such a way that some edges do not leave local DOF. Then, it follows from Proposition 1 that these edges can be removed without destroying the persistence of the merged graph, so that the same collections of meta-vertices can be merged without having connecting edges that do not leave local DOF. In case the meta-vertices are structurally persistent and are merged into a structurally persistent graph, the result still holds as removing edges that do not leave local DOF never destroys structural persistence. The reverse implication is trivial.

The proof of the rest of the result is done as in Theorem 2, using Proposition 5 instead of Theorem 5. \hfill \Box

Merging two meta-vertices into a persistent graph is however a more complicated problem in $\mathbb{R}^3$ than in $\mathbb{R}^2$. Consider a meta-vertex $G_a$ without any DOF, and a meta-vertex $G_b$ which is not structurally persistent, i.e. which is persistent and contains two vertices (leaders) having three DOF. The number of available DOF is equal to the minimal number of edges that should be added to obtain a rigid merged graph. However, the only way to add six edges leaving local DOF is to add three edges leaving each leader of $G_b$ and arriving in $G_a$, as represented by the example in Fig. 5a. Only two vertices of $G_b$ would thus be incident to the added edges, which prevents the merged graph from being rigid and therefore persistent as it is thus.
not 3-connected. We have thus proved the following condition:

**Proposition 6.** If two persistent meta-vertices are such that one is not structurally persistent and the other does not have any DOF, they cannot be merged into a persistent graph by addition of interconnecting edges.

Another problem appears when $G_a$ and $G_b$ each have one leader (having three DOF) and no other vertex has DOF. Again, the number of available DOF is equal to the minimal number of edges that should be added to obtain a rigid merged graph, but the only way to add six edges leaving local DOF does not lead to a rigid graph. One can indeed only add three edges leaving each leader as shown in Fig. 6. This results in a graph that is not 3-connected and therefore not rigid by Theorem 2, as the removal of the two ex-leaders would render the graph unconnected. We thus have the following condition:

**Proposition 7.** If two persistent meta-vertices have each one leader (with three DOF) and no other vertex, they cannot be merged into a persistent graph by addition of interconnecting edges.

However, the following proposition, proved in [25], establishes that these are the only cases for which Proposition 3 cannot be generalized to $|\mathcal{G}|^3$.

**Proposition 8.** Two persistent meta-vertices (each with three or more vertices) can be merged into a persistent graph by addition of directed connecting edges if and only if the sum of their DOF is at least six and the DOF are located on more than two vertices. At least six edges are needed to perform this merging, and merging can always be done with exactly six edges and in such a way that the graph obtained is structurally persistent and does not have all its DOFs located on leaders.

In case at least one of the two meta-vertices has less than three vertices, an exhaustive consideration of all possible cases (see [25]) shows that the result still holds, but with a different required number of edges in $E_M$ and therefore of available DOF: these minimal numbers are both equal to $\min |E_M|$ in Table 1 (for the merging of a graph $G_a(V_a, E_a)$ with a graph $G_b(V_b, E_b)$). Observe that as in the two-dimensional case, the merge can be done in such a way that the number of missing DOF is preserved, the number of missing DOFs being defined in the same way as in Section 3.2, with maximal number of DOF being six, five and three for meta-vertices of respectively $N$, $D$ and $S$. It is worth noting that even if one or both of the meta-vertices are not structurally persistent, it is possible to obtain a structurally persistent merged graph, as in Fig. 5b. This has already been observed in [16] for the case where one meta-vertex is a single vertex graph.

Consider now a collection of meta-vertices such that the total number of vertices is at least three. Unless the collection consists in two meta-vertices satisfying the hypotheses of Proposition 6 or 7, all the graphs that compose it can be merged into one large persistent graph by addition of edges.

**Proposition 9.** A collection of persistent meta-vertices $N \cup D \cup S$ (with $N$, $D$, $S$ as defined in the beginning of this section) containing in total at least three vertices and that does not consist of only two meta-vertices satisfying the condition of Proposition 6 or 7 can be merged into a persistent graph if and only if the total number of missing DOF is no greater than six, or equivalently if the total number of local DOFs in $N \cup D \cup S$ is at least $6|N| + 5|D| + 3|S| - 6$. At least $6|N| + 5|D| + 3|S| - 6$ edges are needed to perform this merging. Merging can
always be done with exactly this number of edges, and in such a way that the merged graph is structurally persistent.

**Proof.** To the exception of some technical arguments related to the possible presence of meta-vertices satisfying the assumptions of Proposition 6 or 7, the proof is similar to the one of Proposition 4. It is presented in detail in [25]. □

As in the two-dimensional case, a merged graph is an edge-optimal persistent merging if and only if it is an edge-optimal rigid merging and all edges in $E_M$ (such as defined in the beginning of this subsection) leave local DOF. The proof of this is an immediate generalization of Theorem 8. However, due to the absence of necessary and sufficient conditions allowing a combinatorial checking of the rigidity of a graph or of a merged graph in $\mathbb{R}^3$, the result cannot be expressed in a purely combinatorial way. Since the number of edges in $E_M$ in an edge-optimal rigid merging is fixed, the above criterion can be re-expressed as

**Theorem 12.** $G = \left( \bigcup_{N,D,S} G_i \right) \cup E_M$ (with $N, D, S$ as defined at the beginning of this section and with all $G_i$ persistent) containing in total at least three vertices is an edge-optimal persistent merging in $\mathbb{R}^3$ if and only if the following conditions all hold:

(i) $G$ is rigid,

(ii) all edges of $E_M$ leave local DOF,

(iii) $|E_M| = 6|N| + 5|D| + 3|S| - 6$.

Again, an efficient way to obtain an edge-optimal persistent merging from a collection of meta-vertices satisfying the hypotheses of Proposition 9 is to first merge two of them and then to iterate, as in the discussion of Propositions 4 and 9.

**V. CONCLUSIONS**

We have analyzed the conditions under which a formation resulting from the merging of several persistent formations is itself persistent. Necessary and sufficient conditions were found to determine which collections of persistent formations could be merged into a larger persistent formation. We first treated these issues in $\mathbb{R}^2$. Our analysis was then generalized to $\mathbb{R}^3$ and to structural persistence, leading to somewhat less powerful results. This is especially the case for those which rely on the sufficient character of Laman’s conditions for rigidity in $\mathbb{R}^2$ (Theorem 1), no equivalent condition being known in $\mathbb{R}^3$. Following this work, we plan to develop systematic ways to build all possible optimally merged persistent formations, similarly to what has been done for minimally persistent formations [26] and for minimally rigid merged formations [27]. These references canvas generalizations of the Henneberg sequence concept [15], [28] for building all minimally rigid graphs in two dimensions.

**REFERENCES**


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