problem	*sub-problem*		*task*	*precondition*	*move*
MF	*FIM*	FIM_1	T_1	*true*	m_1
		FIM_2	T_2	iM3′ ∨ iM3″	m_2
	MRA		T_3	cM	m_3
	FM1		T_4	nM1	m_4
	IM	IM_1	T_5	nM2	m_5
		IM_2	T_6	nM3	m_6
	FM2		T_7	M1	m_7
	MM		T_8	M2	m_8
	MD		T_9	Mf	*nil*

Table 2: Algorithm for *MF*.

is either 1 or 2 (sub-problem FIM_1), whereas T_2 is applied when the symmetricity is 3 (sub-problem FIM_1).

In case of T_1 (see, eg Fig. 2.left), let C_m be the circle of radius $D/2$ centered in $c(R)$. Let r_1 be the robot closest to $c(R)$. Let r_2 be the second robot closest to $c(R)$ (excluding r_1) and, in case of ties, the closest to the line passing through r_1 and $c(R)$, on the other side wrt r_1. If r_1 is outside C_m, it moves radially toward C_m, otherwise r_2 moves radially toward C_m. As soon as r_1 and r_2 are at distance D, they form a molecule and the task is over. Note that, when the symmetricity of the initial configuration is 2, then r_1 and r_2 must be antipodal (as in Fig. 2.left). Hence, they form just one molecule (see, eg Fig. 2.right).

In case of T_2, two different subcases are considered, both leading to the formation of 3 symmetric molecules. The three molecules are formed by means of the most internal robots. The two subcases are based on the preconditions iM3′ and iM3″, see Table 1.

If iM3′ holds, then the distance from $c(R)$ identifies exactly three robots r_1, r_2, r_3. In this case, they first rotate clockwise along C_1^R until they are all aligned with r_1', r_2' and r_3' lying on $C_{R'}$. If they reach such an alignment without creating molecules, then they move radially toward r_1', r_2' and r_3', resp., until forming three molecules.

If iM3″ holds, then there are more than three robots on C_1^R, including r_1, r_2 and r_3. In this case they rotate clockwise along the circle, until three molecules are formed.

Task T_3. This task is used to move all robots (not forming molecules) on C^* (sub-problem Move Robots Away (*MRA*)), as shown in Fig. 2.right. The only molecule formed in T_1 or the three molecules formed in T_2 are used in this task to detect a center from which C^* is identified. In case only one molecule is formed, then C^* is the circle, including all the robots, of minimum radius not smaller than $2mD$ and multiple of $2m$, admitting an annulus A delimited by C^* and a circle of radius $r(C^*) - 3D$ where at most one robot resides. In case three molecules are formed and are included in a circle of radius x, then C^* is the circle, including all the robots, of minimum radius not smaller than $2mD + x$ and multiple of $2m$, admitting an annulus A delimited by C^* and a circle of radius $r(C^*) - 3D$ where at most three robots reside, one for each sector wrt $\rho(Mol)$.

Task T_3 is characterized by precondition cM. In particular, the predicate ensures that one or three molecules have been formed, and in case of one, by ¬iM3′ AND ¬iM3″ no further molecules must be formed. In order to move the robots on C^* we need to define a suitable set T of target points. If $\rho(Mol) = 1$ let L be the line passing through $c(C^*)$ and orthogonal to the segment between the two robots forming the molecule. Let $P = \{p_1, p_2\}$ with p_1 and p_2 being the intersections of L with C^*; If $\rho(Mol) = 3$ instead, let L_1, L_2 and L_3 be the radii of C^* passing through the center of each molecule, then $P = \{p_1, p_2, p_3\}$ with p_1, p_2 and p_3 being the intersections of L_1, L_2 and L_3, resp., with C^*. The set T is defined by all the points at a distance multiple of $\pi r(C^*)/m$ from points in P in the clockwise direction on C^*. Being C^* of radius multiple of $2m$, the points of T are $2m$, including those in P, and equally distributed on C^*. Robots are moved on C^* so as to not create undesired molecules. For each sector, and in a coordinated 3-steps way, the robot furthest from $c(C^*)$ is first moved radially until distance $1.5D$ from C^* (that is in the exact middle of A), then it rotates clockwise until being on the radius of C^* passing through the first unoccupied target, and finally moves radially to the target. Note that there might be at most three robots moving concurrently. The use of A is to be sure that the moving robots do not create molecules accidentally while moving. In fact the width of A is $3D$ and robots move in the middle of A, that is at distance at least $1.5D$ from any other robot.

Task T_4. This task is devoted to the formation of molecules on C^* (sub-problem Forming Molecules 1 (*FM1*)), as shown in Fig. 3.left. The task is needed to assure that T_3 is finished and that the matter can be formed (by means of tasks T_5 or T_6). Hence T_4 can be thought as an auxiliary task exploited to guarantee the evolution of the system from T_3 to T_5 or T_6. In fact, the formation of the matter without creating the molecules handled by T_4 may result in a modification of the definition of C^*.

T_4 is characterized by precondition nM1. If $|Mol'| = 1$, let $X = \{r_1, r_2\}$ be the first two robots that are met from p_1 and p_2, respectively, in the clockwise direction. If $|Mol'| = 3$, let $X = \{r_1, r_2, r_3\}$ be the first three robots that are met from p_1, p_2, and p_3, respectively, in the clockwise direction. Let $R^+ = R \setminus X$. If $|X| = 3$ or ($|X| = 2$ and $\rho(R^+) = 2$), then all robots in X rotate clockwise; otherwise among r_1 and r_2 the farthest from L rotates clockwise.

In doing so, one, two or three molecules are formed on C^* according to the possible initial symmetry deduced from $\rho(R^+)$. Such molecules along with the positioning of the other robots on C^* allow the internal molecules to move to create the core of the matter made by either one or three molecules.

Task T_5 and T_6. These tasks are due to the movement of the first molecules that start the composition of the matter (sub-problem Initialization of the Matter (*IM*)). According whether there are one (as in Fig. 3.right) or three molecules inside C^*, Task T_5 or Task T_6, resp., is executed. The center of C^* is identified by means of the molecules along with all other robots on C^*. Internal molecules can freely move without changing the identification of C^*.

Task T_5 (sub-problem (IM_1)) is characterized by precondition nM2. The unique internal molecule radially moves along L until reaching a position consistent with the center of a molecule forming the matter wrt $c(C^*)$. Note that if the initial configuration was admitting symmetricity 2, after T_5 the configuration becomes asymmetric.

Task T_6 (sub-problem (IM_2)) is characterized by precondition nM3. The three internal molecules first rotate clockwise wrt to their center until the radii of C^* passing through their centers become orthogonal to the segments joining the two robots forming

move	*definition*
m_1	Let C_m be the circle of radius $D/2$ centered in c_m that coincides with $c(R)$. Let r_1 be the robot closest to c_m (of minimum view in case of ties) and r_2 be the robot closest to c_m (excluding r_1) and the closest to the line passing through r_1 and c_m, on the other side wrt r_1 in case of ties. If r_1 is outside C_m, it moves radially on C_m, otherwise r_2 moves radially toward C_m.
m_2	If iM3′ holds: r_1, r_2 and r_3 rotate until they are all aligned with r'_1, r'_2 and r'_3. If they reach such an alignment without creating molecules, then they move radially toward r'_1, r'_2 and r'_3, resp.; if iM3″ holds, then r_1, r_2 and r_3 rotate clockwise.
m_3	For each sector, and in a coordinated 3-steps way, the robot furthest from $c(R)$ is first moved radially until distance $\frac{3}{2}D$ from C^* (that is in the exact middle of A), then it rotates clockwise until being on the radius of C^* passing through the first unoccupied target, and finally moves radially to the target.
m_4	If $\|X\| = 3$ or ($\|X\| = 2$ and $\rho(R^+) = 2$), then all robots in X rotate clockwise; otherwise among r_1 and r_2 the farthest from L rotates clockwise.
m_5	The unique internal molecule radially moves along L until reaching a position consistent with a molecule forming the matter wrt $c(C^*)$.
m_6	The three internal molecules first rotate clockwise wrt to their center until the radii of C^* passing through their centers become orthogonal to the segments joining the two robots forming each molecule. Then, they radially move until reaching the right positioning in order to become part of the matter wrt $c(C^*)$.
m_7	If the matter is currently composed by at least three molecules, then let r_1, r_2 and r_3 be the first three robots met from p_1, p_2, and p_3, respectively, in the clockwise direction. If $\rho(R \setminus \{r1, r2, r3\}) = 3$ then r_1, r_2 and r_3 rotate along C^* until creating three molecules. If $\rho(R \setminus \{r1, r2, r3\}) \neq 3$, then the robot among r_1, r_2, and r_3 closest to the successive one in the clockwise direction rotates along C^* until forming a new molecule.
m_8	This task moves all the molecules formed by means of task T_7 to grow the matter. The molecule closest in the clockwise direction to the first available position of the last level of the matter not yet filled, moves there clockwise while possibly rotating wrt its center.

Table 3: Moves associated with tasks.

each molecule. Then, they radially move until reaching the right positioning in order to become part of the matter wrt $c(C^*)$.

Once T_5 or T_6 terminate, the matter is suitably initialized and the configuration admits a symmetricity of either 1 or 3, respectively.

Task T_7. This task forms new molecules on C^* (sub-problem Forming Molecules 2 (*FM2*)) that afterward are moved by T_8 so as to make the matter growing (see, eg Fig.s 4 and 5). If the matter is currently composed by at least three molecules, then let r_1, r_2 and r_3 be the first three robots met from p_1, p_2, and p_3, resp., in the clockwise direction. If the symmetricity of the configuration excluding r_1, r_2 and r_3 is 3, then r_1, r_2 and r_3 rotate along C^* until creating three molecules. If such a symmetricity is not 3 or the matter is currently composed by less than three molecules, then the robot on C^* closest to the successive one in the clockwise direction rotates along C^* until forming a new molecule.

Task T_8. This task moves all the molecules formed on C^* by means of tasks T_4 or T_7 to grow the matter (sub-problem Moving Molecules (*MM*)), see, eg Fig. 4. The molecule closest in the clockwise direction to the first available position of the last level of the matter not yet filled, moves there clockwise while possibly rotating wrt its center.

Task T_9. It refers to the requirement of letting molecules to detect the matter has been formed, hence no more movements are required (sub-problem Matter Done (*MD*)). Clearly, only *nil* movements are allowed and it is not possible to switch to any other task.

3.3 Running example

In this section, we show how robots correctly detect the task to perform. According to the definitions of P_i given in Eq. 1, in the Compute phase, each robot evaluates – wrt the perceived configuration – the preconditions starting from P_9 and proceeding in the reverse order until a true precondition is found. In case all preconditions $\mathtt{pre}_9, \mathtt{pre}_8, \ldots, \mathtt{pre}_2$ are evaluated false, then task T_1, whose precondition is simply true, is performed. It follows that the algorithm satisfies $\mathtt{Prop}_3$.

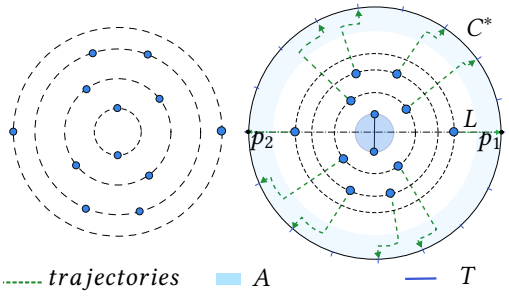

Figure 2: Configurations belonging to tasks T_1 (left) and T_3 (right). Relative distances are reduced for space constraints.

The initial configuration in Fig. 2.left is such that $\rho(R) = 2$ and belongs to T_1. In fact, since there are no molecules formed, Mf, M2, M1, nM3, nM2, nM1, and cM are false, that is the configuration is not in $T_9, \ldots T_3$, respectively. Concerning iM3″, circle C_R contains only two robots, hence the predicate is false. Concerning iM3′, the distance from $c(R)$ detects 6 robots, hence the predicate is false too, that is the configuration is not in T_2 and then belongs to T_1. During T_1 the two most internal robots move toward each other according to m_1, hence the same considerations as above hold until their distance reduces to D and a molecule is formed, see Fig. 2.right.

The reached configuration in Fig. 2.right belongs to T_3. In fact, Mf is clearly false, that is the configuration is not in T_9. As FarC is false, that is FarC is false (see Table 1), then M2, M1, nM3, nM2, and nM1 are false, that is the configuration in not in $T_8, \ldots T_4$, respectively. Concerning iM3″, circle C_R contains only two robots, hence the predicate is false. Concerning iM3′, the distance from $c(R)$ detects 6 robots, hence the predicate is false too. Since $|Mol| = 1$ and not all the robots are on C^* then cM is true, that is the configuration belongs to T_3. In Fig. 2 also the trajectories traced by the robots are shown during T_3 and the above Boolean values hold until the

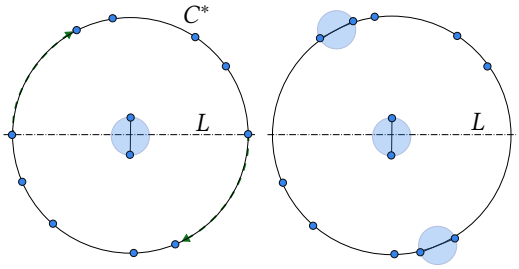

Figure 3: Configurations in tasks T_4 (left) and T_5 (right).

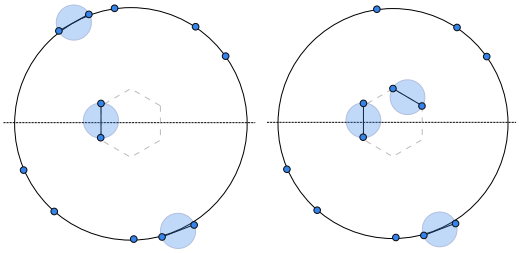

Figure 4: Two successive configurations belonging to task T_8.

last robot reaches C^*. In particular, for iM3′ it is possible that at some point the distance from $c(R)$ identifies exactly three robots, however, in that case $\rho(R') < 3$.

The reached configuration in Fig. 3.left belongs to T_4. In fact, here $Mat = \emptyset$, hence Mf, M2, M1, are false and the configuration is not in T_9, T_8, nor T_7. As $|Mol| = 1$ then nM3 and nM2 are false, that is the configuration does not belong to T_6 nor T_5. Since $|Mat| = 0$, FarC is true, $|Mol'| = 1$ and there are no molecules on C^* then nM1 is true and the configuration is in T_4. The corresponding move m_4 makes robots on p_1 and p_2 rotate clockwise on C^* until forming two molecules. During the movements, it is possible that one molecule appears before the other but this does not affect the truth value of the above predicates.

The reached configuration in Fig. 3.right belongs to T_5. In fact, here $Mat = \emptyset$, hence Mf, M2, M1, are false and the configuration is not in T_9, T_8, nor T_7. As $|Mol| = 3$ then nM3 is false, that is the configuration does not belong to T_6. Since $|Mat| = 0$, FarC is true, $|Mol| = 3$ with 1 or 2 molecules on C^* and 1 internal, and the number of molecules on C^* is no more than $\rho(R)$ then nM2 is true and the configuration is in T_5. Here the internal molecule radially move along L reaching the side of an hexagon of side D centered in $c(C^*)$, hence making $|Mat| = 1$. During the movements the truth value of the above predicates is not affected. The reached configuration in Fig. 4 belongs to T_8. In fact, here Mf is false, that is the configuration is not in T_9. Since $|Mat| > 0$, FarC is true, $|Mol \setminus Mat| = 2$ and the matter does not admit a rotation, then M2 holds and the configuration is in T_8. Move m_8 involves the two external molecules, one by one, and leads them to be part of the matter. During the movements and after the first molecule arrives, $|Mol \setminus Mat| = 1$ and $\rho(R \setminus \{r_1, r_2, r_3\}) = 1$, hence the truth value of the above predicates is not affected. The reached configuration in Fig. 5 belongs to T_7. In fact, here Mf is false, that is the configuration is not in T_9. $|Mol| \setminus |Mat| = 0$, that is M2 is false the configuration

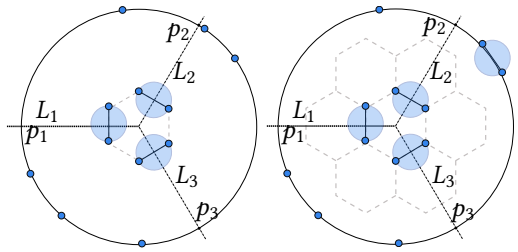

Figure 5: Configurations in tasks T_7 (left) and T_8 (right).

is not in T_8. Since $|Mat| > 0$, $|Mol \setminus Mat| < 3$ and FarC is true then M1 holds and the configuration is in T_7. This holds also during the movement of the robots.

It is easy to see that the reached configuration belongs again to T_8 and by alternating with T_7 the final configuration in Fig. 1.left is achieved. According to precondition *MF*, the final configuration belongs to Task T_9, where only the *nil* movement is performed.

The reached configuration admits symmetricity 1 whereas the initial configuration of Fig. 2.left has symmetricity 2. According to Theorem 2.1, this is possible since $\rho(\mu) = 2$. Contrarily, within OBLOT, the disposal of the robots as specified by the defined matter could not be achieved. However, when each molecule in $\mathcal{M}$ is constituted by a single robot, then MOBLOT reduces to OBLOT.

4 CONCLUSION

In this paper, we have proposed MOBLOT, a new theoretical model in the context of swarm robotics that extends OBLOT. MOBLOT concerns two levels of computational entities: robots and molecules. Robots can be very weak entities like in the OBLOT model, although here they can be heterogeneous; molecules are more complex entities with an extent. Robots and molecules are guided by their respective distributed algorithms: the former is used to form molecules, the latter to assemble molecules to obtain some complex structure, the matter. Once the matter is formed, a third algorithm could even be used to rearrange (self-reconfigure) the molecules' positions to get a different shape for the matter.

We have proven that there is some necessary condition for forming the matter. This condition states that the symmetricity of the initial configuration of robots must divide either the symmetricity of some molecule, or the symmetricity of the matter to be formed. Interestingly, this implies that the matter could be formed even when the symmetricity of the input configuration is unrelated to that of the matter (in such cases, the molecules play a decisive role).

There are many directions for future research in the proposed model. The most obvious one is to investigate about a (complete) characterization of the solvability of the matter formation problem according to the assumed capabilities for robots and molecules. Others concern the formalization of possible self-reconfigurable matter problems, as well problems related to the matter movement.

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