Automatic Detection of Subassemblies for Disassembly Sequence Planning

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Keywords: Remanufacturing, Disassembly Planning, Dismantling, Robotic Disassembly.

Abstract: Disassembly, the first process in remanufacturing, is labour-intensive due to the conditions of end-of-life products returned for remanufacture. Robotic disassembly is an attractive alternative to manual disassembly but robotic systems cannot plan disassembly sequences automatically and manual planning is still required. Several planning methods have been proposed to take away removable components sequentially. However, those methods do not work when it is required to break an assembly into subassemblies. This paper proposes a method for automatic detection of subassemblies. The approach starts with using an assembly matrix and simple logic gates to generate a contact matrix and a relation matrix. The paper details new algorithms used to detect subassemblies through manipulating the two matrices.

1 INTRODUCTION

Remanufacturing is "the rebuilding of a product to specifications of the original manufactured product using a combination of reused, repaired and new parts" (Johnson and McCarthy, 2014). One important feature distinguishing remanufacturing from conventional manufacturing is disassembly. Due to the variability in the condition of the returned products, disassembly tends to be manually carried out. It is labour intensive, given the complexity of the operations involved.

Developments in automated disassembly systems started in the mid-1990s with the robotic disassembly of a PC (Kopacek and Kronreif, 1996), followed by several successful attempts at dismantling electrical devices and automotive components (Barwood *et al.*, 2015; Gil *et al.*, 2007; Vongbunyong and Chen, 2015). The reported experiments were mostly product-orientated and based on pre-programmed sequences. A key advance from ‘automated’ disassembly to ‘autonomous’ disassembly would be that machines plan disassembly sequences using the structure of the product rather than following a pre-programmed sequence. A popular approach is based on graphs (Li *et al.*, 2002; Torres *et al.* , 2003). Many algorithms and rule-based methods have been used to calculate disassembly sequences, for example, the Fuzzy Reasoning Petri Net proposed by Zhao and Li (Zhao and Li, 2010). However, the generation of a graph relies on human understanding instead of machine interpretation.

Smith *et al.* presented a tool consisting of five matrices to represent an assembly and used several rules to generate disassembly sequences (Smith and Chen, 2009; Smith *et al.*, 2012). Tao *et al.* also modified the matrices to enable partial/parallel

Wang, Y., Lan, F., Pham, D., Liu, J., Huang, J., Ji, C., Su, S., Xu, W., Liu, Q. and Zhou, Z.
Automatic Detection of Subassemblies for Disassembly Sequence Planning.
DOI: 10.5220/0006906600940100
In *Proceedings of the 15th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2018) - Volume 1*, pages 94-100
ISBN: 978-989-758-321-6

disassembly (Tao *et al.*, 2017). However, this optimisation-focused work did not reduce the complexity of the mathematical representation of an assembly in which distinguishing between fasteners and general parts was needed although their definitions were fuzzy and could cause confusion in many cases. For example, it is not clear whether to categorise objects in press-fit components as fasteners or general parts. Another matrix-based example can be found in the work of Jin *et al.* (Jin *et al.*, 2015; Jin *et al.*, 2013), in which the relationships between components were presented using just a matrix. However, the matrix-based methods tend to focus on sequential disassembly and cannot work correctly when breaking an assembly into subassemblies is required.

This paper presents a method that can detect subassemblies automatically. Based on an analysis of over 239 mechanical products by the authors' team, breaking into subassemblies is a critical step for some 23% of them (Ji *et al.* 2017), and cannot be correctly dealt with using conventional methods.

Section 2 presents the definitions and derivations of two matrices: contact and relation matrix, which can represent the contact status of components. Such information can be used to identify separable pairs, pairs of components which can be broken to build subassemblies (Section 3). A case study is given in Section 4 to demonstrate the use of the approach.

2 CONTACT AND RELATION MATRICES: FUNDAMENTAL TOOLS

Jin *et al.* (Jin *et al.*, 2015; Jin *et al.*, 2013) demonstrated a method to identify removable components to generate feasible disassembly sequences using the space interference matrix. The essence of the approach is to find components that have freedom in at least one direction, indicating that the components are removable. A product can be disassembled after multiple cycles of taking away removable components step-by-step in a sequential way.

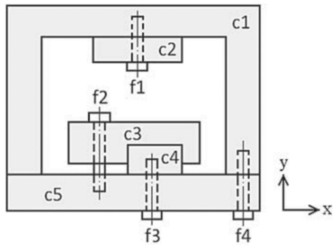


Figure 1: An example product.

If the method is adopted for the case in Figure 1 (Smith and Hung, 2015), however, after the removal of f_3 and f_4 in the first step, no components can be further disassembled, as shown in Figure 2. This is a typical interlocking structure. An assembly cannot be disassembled as no parts are removable until the whole structure is broken into smaller subassemblies.

The paper proposes the contact matrix and relation matrix, as fundamental tools to detect subassemblies. It can represent contact conditions in an assembly in six directions (X+, X-, Y+, Y-, Z+, Z-). Here, only four directions (X+, X-, Y+, Y-) are needed for demonstrations in two dimensions, as shown in Eq. 1.

In the matrix, C_n represents components in an assembly. $r_{nn.x+}$, $r_{nn.x-}$, $r_{nn.y+}$, and $r_{nn.y-}$ indicate the contact status of the components in the corresponding columns and rows by using two states: 0 for no contact and 1 for contact. For example, the assembly in Figure 1 can be represented by the contact matrix in Eq. 2. $r_{12.x+}r_{12.x-}r_{12.y+}r_{12.y-}$ is 0001 because C_2 is a contact in Y- direction for C_1. C_1 can be removed from C_2 in Y+ direction. Similarly, $r_{21.x+}r_{21.x-}r_{21.y+}r_{21.y-}$ is 0010 because C_1 a contact in Y+ direction for C_2. C_2 can be removed from C_1 in Y- direction. It is worth noting that symmetry may not be observed in $r_{ab.x+}r_{ab.x-}r_{ab.y+}r_{ab.y-}$ and $r_{ba.x+}r_{ba.x-}r_{ba.y+}r_{ba.y-}$ due to requirements of proper disassembly operations. For example, $r_{61.x+}r_{61.x-}r_{61.y+}r_{61.y-}$ is 1110 and $r_{16.x+}r_{16.x-}r_{16.y+}r_{16.y-}$ is 1111, because removing f_1 from C_1 is a proper operation but the reverse is not.

The relation matrix describes the general contact status of components, derived from contact matrix (Figure 3). The two matrices could be the keys for a machine to understand subassemblies.

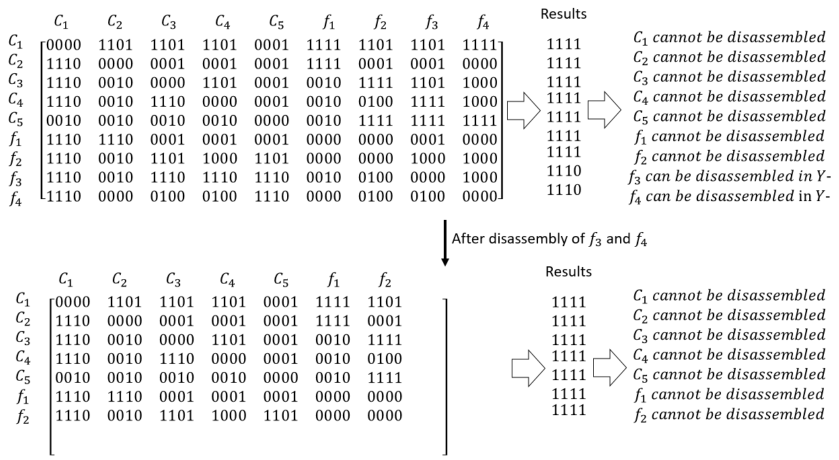


Figure 2: Sequential disassembly method proposed by Jin *et al.* (Jin *et al.*, 2015; Jin *et al.*, 2013).

$$C = \begin{array}{c} \\ C_1 \\ \vdots \\ C_n \end{array} \begin{array}{c} \begin{array}{ccc} C_1 & \dots & C_n \end{array} \\ \begin{bmatrix} r_{11.x+}r_{11.x-}r_{11.y+}r_{11.y-} & \cdots & r_{1n.x+}r_{1n.x-}r_{1n.y+}r_{1n.y-} \\ \vdots & \ddots & \vdots \\ r_{n1.x+}r_{n1.x-}r_{n1.y+}r_{n1.y-} & \cdots & r_{nn.x+}r_{nn.x-}r_{nn.y+}r_{nn.y-} \end{bmatrix} \end{array} \quad (1)$$

$$C= \begin{array}{c} \\ C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \\ f_1 \\ f_2 \\ f_3 \\ f_4 \end{array} \begin{array}{c} \begin{array}{ccccccccc} C_1 & C_2 & C_3 & C_4 & C_5 & f_1 & f_2 & f_3 & f_4 \end{array} \\ \begin{bmatrix} 0000 & 0001 & 0000 & 0000 & 0001 & 1111 & 0000 & 0000 & 1111 \\ 0010 & 0000 & 0000 & 0000 & 0000 & 1111 & 0000 & 0000 & 0000 \\ 0000 & 0000 & 0000 & 1101 & 0000 & 0000 & 1111 & 0000 & 0000 \\ 0000 & 0000 & 1110 & 0000 & 0001 & 0000 & 0000 & 1111 & 0000 \\ 0010 & 0000 & 0000 & 0010 & 0000 & 0000 & 1111 & 1111 & 1111 \\ 1110 & 1110 & 0000 & 0000 & 0000 & 0000 & 0000 & 0000 & 0000 \\ 0000 & 0000 & 1101 & 0000 & 1101 & 0000 & 0000 & 0000 & 0000 \\ 0000 & 0000 & 0000 & 1110 & 1110 & 0000 & 0000 & 0000 & 0000 \\ 1110 & 0000 & 0000 & 0000 & 1110 & 0000 & 0000 & 0000 & 0000 \end{bmatrix} \end{array} \quad (2)$$

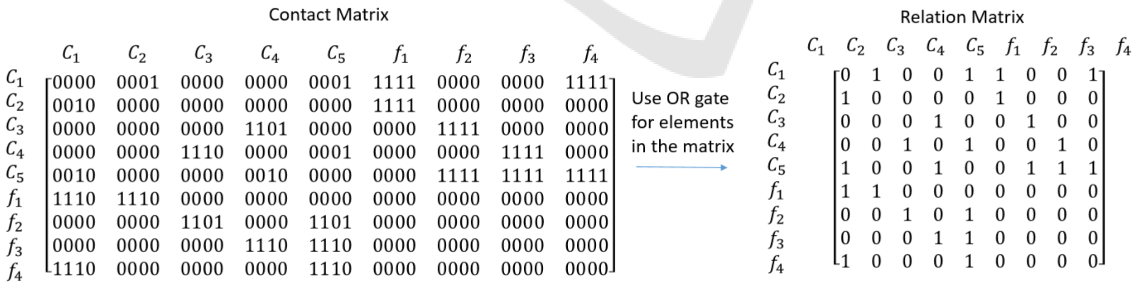
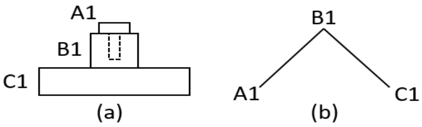


Figure 3: Derivation of a relation matrix from a contact matrix.

3 SEPARABILITY CHECK

3.1 Definition of Separability

The separability of an assembly indicates whether it can be broken into subassemblies. The separability of an assembly is determined by whether it contains 'separable pairs', pairs of contacting components that can be separated without affecting other contacting components. For example, the assembly in Figure 4a has three components: A1, B1 and C1, and two pairs of contacting components: A1-B1 and B1-C1. If a contact between a pair can be represented as a line, then the physical model in Figure 4a can be simplified to Figure 4b, which can also be represented by its relation matrix (R1), as shown in Figure 4c. Both pairs, A1-B1 and B1-C1, are separable, as the separation of either pair would not affect the other.

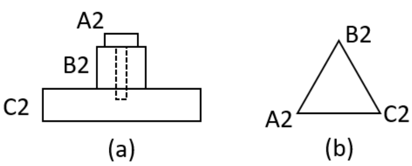


$$R1 = \begin{matrix} & A1 & B1 & C1 \\ A1 & 0 & 1 & 0 \\ B1 & 1 & 0 & 1 \\ C1 & 0 & 1 & 0 \end{matrix}$$

(c)

Figure 4: An example of a product comprising separable pairs.

However, in a similar model shown in Figure 5, the result would be different. None of the three pairs, A2-B2, B2-C2 and A2-C2, are separable, as the separation of a pair could affect other pairs. For example, the separation of A2-B2 inevitably causes the detachment of A2 from C2. Comparing Figure 4b to Figure 5b, it is obvious that there is only one path between A1 and B1 (A1-B1) in Figure 4b, but there are two paths between A2 and B2 (A2-B2, and A2-C2-B2) in Figure 5b. When there is only one path, the interaction between the two components is not coupled with those with other components. A sufficient condition for a pair to be separable is that there is only one path between two components in a pair, as in the pairs A1-B1 and B1-C1 in Figure 4b.



$$R2 = \begin{matrix} & A2 & B2 & C2 \\ A2 & 0 & 1 & 1 \\ B2 & 1 & 0 & 1 \\ C2 & 1 & 1 & 0 \end{matrix}$$

(c)

Figure 5: An example of a product comprising inseparable pairs.

3.2 Separable Pairs Search Process

Separable pairs can be searched for using vectors, namely node vectors, to represent components, as shown in Eq. 3, so that the links connected to a node can be calculated by multiplying the relation matrix R1 with its note vector (Eq. 4 to 6).

$$A1 = \begin{bmatrix}1\\0\\0\end{bmatrix}, B1 = \begin{bmatrix}0\\1\\0\end{bmatrix}, C1 = \begin{bmatrix}0\\0\\1\end{bmatrix} \tag{3}$$

$$\mathrm{R1}.A1 = \begin{bmatrix}0&1&0\\1&0&1\\0&1&0\end{bmatrix} \cdot \begin{bmatrix}1\\0\\0\end{bmatrix} = \begin{bmatrix}0\\1\\0\end{bmatrix} = B1, \tag{4}$$

$$\mathrm{R1}.B1 = \begin{bmatrix}0&1&0\\1&0&1\\0&1&0\end{bmatrix} \cdot \begin{bmatrix}0\\1\\0\end{bmatrix} = \begin{bmatrix}1\\0\\1\end{bmatrix} = A1 + C1, \tag{5}$$

$$\mathrm{R1.C1} = \begin{bmatrix}0&1&0\\1&0&1\\0&1&0\end{bmatrix} \cdot \begin{bmatrix}0\\0\\1\end{bmatrix} = \begin{bmatrix}0\\1\\0\end{bmatrix} = B1 \tag{6}$$

The method can be used to identify adjacent components. Also, a path between two nodes can be found by recursively multiplying the relation matrix by a node vector and its adjacent node vectors until a destination is reached. Figure 6 shows the process of searching for separable pairs using a relation matrix.

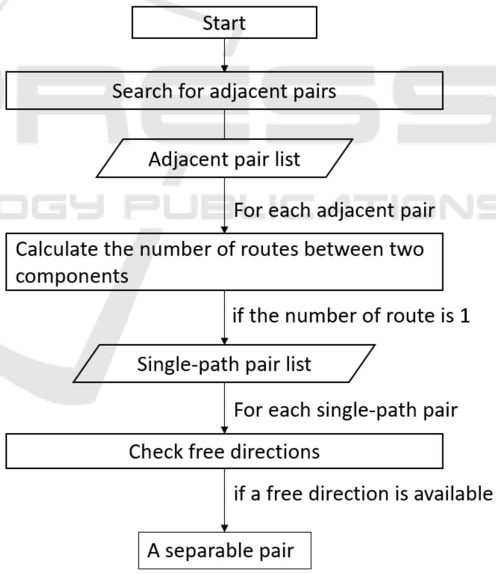


Figure 6: Separable pairs search process.

The first step is to search for adjacent pairs, two components in contact, which can be identified using Eq. 3 to 6.

The second step is to identify the pair in which there is only one route between the two components, a sufficient condition for a pair to be separable, as discussed earlier. We propose using a recursive strategy using the pseudo code in Algorithm 1.

Algorithm 1: Generate single-path pair list from adjacent pair list.

```
Main function:
Input:  adjacent pair list (APL)
Output: Single-path list (SPL)
For every pair {X, Y} Є APL
  counter = 0
   searchPath(X,Y) ;
   If counter = 1
     add {X, Y} to SPL;
   End if
End for

searchPath(X,Y)
Label X as discovered
For every component k adjacent to X
  If k is not labelled as discovered
   If k = Y
     counter++;
     If counter >=2
       break;
     End if
   Else
     Recursively call searchPath(k,Y)
   End if
  End if
Return counter
End for
```

After all single-path pairs are identified, their corresponding elements in the contact matrix should be checked. If the elements are not 1111 ($r_{ab.x+}r_{ab.x-}r_{ab.y+}r_{ab.y-}$ ≠1111 and $r_{ba.x+}r_{ba.x-}r_{ba.y+}r_{ba.y-}$ ≠1111), it indicates that one component has freedom on at least one direction in relation to the other, and thus the pair is separable. Details are explained using the discussed example in Figure 1.

After the removal of f_3 and f_4, the node-line model of the assembly and its relation matrix are presented in Figure 7 and Eq. 7. By using Eqs.3 and 4, eight adjacent pairs can be identified: C1-C2, C1-C4, C2-C3, C2-f1, C3-C4, C4-C5, C5-f1 and C5-f2.

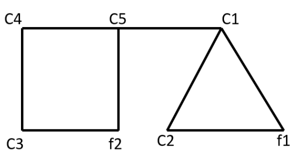


Figure 7: Model of the assembly after the removal of f3 and f4.

$$R = \begin{array}{c} C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \\ f_1 \\ f_2 \end{array} \overset{\begin{array}{ccccccc} C_1 & C_2 & C_3 & C_4 & C_5 & f_1 & f_2 \end{array}}{\begin{bmatrix} 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 \end{bmatrix}} \quad (7)$$

Algorithm 1 is used to calculate the number of routes between two components in a pair, starting from the first pair C1-C2. The result indicates that the pair is not separable, as there are two routes from C1 to C2 (C1→C2 and C1→f1→C2), as depicted in Figure 8. For the next member on the adjacent pair list, C1-C5, only one route is found, and thus the pair is added to single-path list. The calculation continues for all pairs on the adjacent pair list, and C1-C5 is the only single-path pair. As C1 and C5 have freedom in 3 directions, the pair is a separable pair.

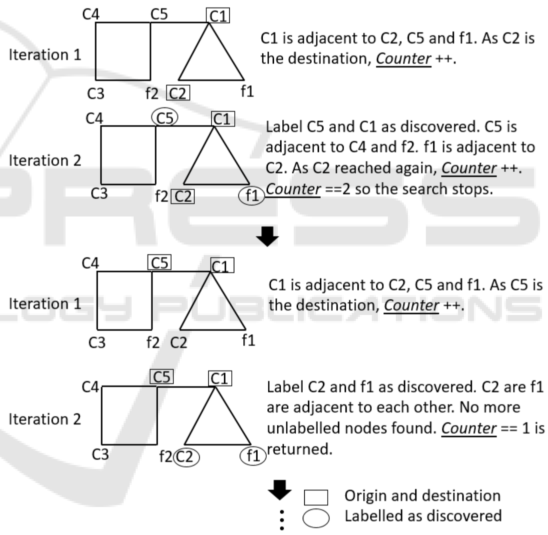


Figure 8: An example of searching for single-path pairs.

It indicates that the separation of C1 and C5 would result in two subassemblies: C1-C2-f1 and C3-C4-C5-f2. Then, f2 and f1 become removable and disassembly iterations could carry on using sequential disassembly planning methods.

4 CASE STUDY

This section discusses a case study of the disassembly of a piston used in a 4-stroke engine, as shown in Figure 9.

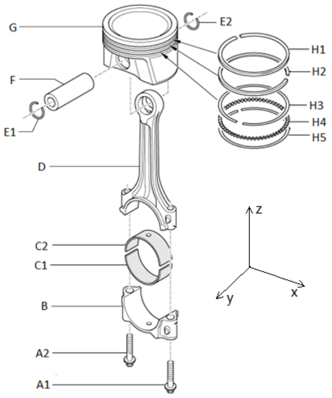


Figure 9: Parts in a piston.

If the conventional sequential disassembly method (G. Jin *et al.*, 2015; G. Q. Jin *et al.*, 2013) is adopted, the sequential disassembly plan as shown in table 1 is obtained using the space interference matrix (Appendix). It can be seen that no removable parts are identified at iteration 7, and parts B, C1-2 and D form an interlocking structure. To continue disassembly, the methods presented in Section 3 can be employed to identify a separable pair to break the product into subassemblies.

Table 1: Sequential disassembly plan generated using the method by Jin *et al.*

Iteration	Removable parts	Remaining parts
1	A1-111110 A2-111110 E1-110111 E2-111011 H1-111101	B, C1-2, D, F, G, H2-5
2	F -110011 H2 - 111101	B, C1-2, D, G, H3-5
3	H3 - 111101	B, C1-2, D, G, H4-5
4	H4 - 111101	B, C1-2, D, G, H5
5	H5 - 111101	B, C1-2, D, G
6	G - 111101	B, C1-2, D
7	None	B, C1-2, D

The contact matrix and related matrix of the structure B-C1-C2-D are given in Eqs. 8 and 9. By using Eq. 3 to 6, three adjacent pairs can be identified: B-C1, B-D and C2-D. Algorithm 1 is used to calculate the number of routes between two components in a pair. The result indicates that all three pairs are single-path pairs. However, only B-D is a separable pair as C_{12} and C_{43} are 111111, indicating that either B-C1 or C2-D has no freedom to separate. The separation of B and D builds two subassemblies, B-C1 and C2-D, and thus further disassembly operations can carry on.

$$C=\begin{matrix} & B & C1 & C2 & D \\ B \\ C1 \\ C2 \\ D \end{matrix}\begin{bmatrix} 000000 & 111111 & 000000 & 000010 \\ 111101 & 000000 & 000000 & 000000 \\ 000000 & 000000 & 000000 & 111110 \\ 000001 & 000000 & 111111 & 000000 \end{bmatrix} \quad (8)$$

$$R=\begin{matrix} B \\ C1 \\ C2 \\ D \end{matrix}\overset{\begin{matrix} B & C1 & C2 & D \end{matrix}}{\begin{bmatrix} 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{bmatrix}} \quad (9)$$

5 CONCLUSION

Machine understanding of the structure of an assembly in three-dimensional space is required for autonomous disassembly planning. Conventionally, because of the complexity of spatial information, models tended to be complex and normally not suitable for all structures, in particular, those containing interlocking components. As far as the authors are aware, no previous work has been carried out relating to this issue.

This paper presents a method to break an assembly into subassemblies when sequential disassembly of components is not possible. The method is designed to work for all subassemblies containing interlocking components and its effectiveness was demonstrated with a case study.

Future work could investigate combining the proposed method with conventional disassembly planning approaches. This would undoubtedly yield a more capable disassembly planning system suitable for adoption in autonomous remanufacturing.

ACKNOWLEDGEMENT

This research was supported by the EPSRC (Grant No. EP/N018524/1) and the National Science Foundation of China (Grant No. 51775399).

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APPENDIX

Space interference matrix

	A1	A2	B	C1	C2	D	E1	E2	F	G	H1	H2	H3	H4	H5
A1	000000	010000	111110	010000	010000	111110	000000	000000	000000	000010	000010	000010	000010	000010	000010
A2	100000	000000	111110	100000	100000	111110	000000	000000	000000	000010	000010	000010	000010	000010	000010
B	111111	111111	000000	111111	000010	000010	000000	000000	000010	000010	000010	000010	000010	000010	000010
C1	100000	010000	111101	000000	000010	000010	000000	000000	000010	000010	000010	000010	000010	000010	000010
C2	100000	010000	000001	000001	000000	111110	000000	000000	000010	000010	000010	000010	000010	000010	000010
D	111111	111111	000001	000001	111111	000000	001000	000100	110011	111110	000010	000010	000010	000010	000010
E1	000000	000000	000000	000000	000000	000100	000000	000100	000100	110111	000000	000000	000000	000000	000000
E2	000000	000000	000000	000000	000000	001000	001000	000000	001000	111011	000000	000000	000000	000000	000000
F	000000	000000	000001	000001	000001	110011	001000	000100	000000	110011	000000	000000	000000	000000	000000
G	000001	000001	000001	000001	000001	111101	111111	111111	111111	000000	111111	111111	111111	111111	111111
H1	000001	000001	000001	000001	000001	000001	000000	000000	000000	111101	000000	000001	000001	000001	000001
H2	000001	000001	000001	000001	000001	000001	000000	000000	000000	111101	000010	000000	000001	000001	000001
H3	000001	000001	000001	000001	000001	000001	000000	000000	000000	111101	000010	000010	000000	000001	000001
H4	000001	000001	000001	000001	000001	000001	000000	000000	000000	111101	000010	000010	000010	000000	000001
H5	000001	000001	000001	000001	000001	000001	000000	000000	000000	111101	000010	000010	000010	000010	000000