An Original Approach for Translating Grafcet into C/Unix Code for Validation Purposes

Nacera Benaouda
Department of Computer Science
Ferhat Abbas University Setif I
Setif, Algeria
nacbenaouda@univ-setif.dz

Abdelhafid Benaouda
Department of Computer Science
Ferhat Abbas University Setif I
Setif, Algeria
ahbenaouda@univ-setif.dz

Received: 19 September 2022 | Revised: 3 October 2022 | Accepted: 6 October 2022

Abstract-This paper proposes an approach to simulate the function of the control part of a Grafcet model, translating it into C code in a Unix environment. First, the Grafcet/C generation schemes are established. The Grafcet model, described in graphic or text form, is transformed in an internal form and then to C code by a generation algorithm based on the previously found diagrams. The result is a program that simulates the operation of the automation in question and makes it possible to validate the functional specifications of sequential automation. This validation can be used for educational purposes, such as the learning of the Grafcet formalism, or corrective or evolutionary maintenance. Once the configuration, testing, and validation of the program are complete, it is possible to implement the object code on the microcontroller of the control system.

Keywords-C/Unix; Grafcet; process; sequential automation

I. INTRODUCTION

Equipment manufacturers and automation engineers responsible for automated industrial installations should master the programs that drive their installations to perform preventive [1, 2], corrective, adaptive, and evolutionary maintenance tasks [3]. These programs are often outsourced, use a variety of libraries, and depend not only on the problem to be solved but also on the past of their provider. Grafcet [4, 5] is a graphic formalism for describing automatisms, accepted by mechanical automation engineers who consider it to represent the right level of specification without much complexity. In an automated system, the control part is the image of the operative part that represents the automated machine. Simulation and validation of the operation of an automated system are necessary before its implementation in the actual installation. Simulating the operation of Grafcet is equivalent to translating it into appropriate languages, which generate programs with the same semantics. These programs have shown their usefulness for maintenance or educational purposes. This study chose C/Unix as the target language and system for the Grafcet translation. This choice was motivated by two reasons; the C language extended by the Unix libraries has all the necessary tools for the translation of Grafcet, and the required hardware and software configuration for the application is very simple, just a personal computer with a Linux distribution.

II. RELATED WORK

Several studies achieved to formalize Grafcet. In [6], Grafcet translation schemes were designed in the Occam2 language, which is executable on transputers, exploiting the possibilities of expressions of parallel tasks offered in Occam2 to express the respective representation in Grafcet. The resulting program could run on a parallel machine and simulate the actual operation of an automated system. This work could obtain the equivalent Occam2 program from a Grafcet in graphical or textual form. Being a parallel language, Occam2 possesses the necessary tools to translate Grafcet, but the resulting program can only be exploited if a parallel machine existed. Since parallel machines are only available in certain research laboratories or specific industrial settings, such a program may have limited use. In [7], a semi-coarse ontology was defined and tested by integrating it into an existing educational tool to teach Grafcet for use in programmable logic controllers. This ontology was OWL (Web Ontology Language) DL based, a specific decidable fragment of first-order logic applied to OWL markup language. The objective of this method was to complement previous studies and promote this type of technique in the formalization of Grafcet. The advantages of ontologies are numerous, as they make collaboration and sharing of knowledge easier, provide better reliability, and assure to handle automatically any input change without having to recompile the processing code. This approach was validated according to two criteria, accuracy and completeness. A new vision was adopted in [8], by proposing a systematic implementation of the control software in IEC 61499. This constituted a key advantage over previous Grafcet implementations because it allowed engineers to implement models distributed over several devices and also kept the initial centralized design. IEC 61499 has all the translation tools for most of the Grafcet elements. This work made it possible to systematically translate Grafcet and introduced several translation models. The disadvantages of this method lied in the fact that it was not possible to model the structuring mechanisms such as fences or forcing steps, and the macros-steps that could be implemented were limited to simple sequences.

Corresponding author: Nacera Benaouda

III. MOTIVATION FOR CHOOSING C LANGUAGE

Grafcet is a logical automatism description formalism that allows expressing competing processes. A language to translate Grafcet has to preferably be parallel [6] and/or real-time. The duration of the task's installation or its switching time is decisive in choosing such a language. C and Unix [9] were chosen due to their portability, universality, and control by most computer scientists. Its disadvantage lies in the fact that Unix is not quite real-time, because its slow temporal primitives were defined according to the only problems of the timeshare. C language is a High-Level Machine-Oriented Language (HLMOL) that allows defining bit-close fields, and expanded by Unix libraries can provide the illusion of simultaneous execution of tasks on uniprocessor machines, as shown by functions such as fork, wait, sleep, kill [9]. Pipes are the main means of communication between Unix processes [9]. Several synchronization means are available in Unix. This study used the wait function, which is the most basic mean of synchronization and can be used to synchronize a parent process on the termination of its children. Time management was carried out using the sleep() function, as the call to the sleep(*n*) function suspends the calling process for *n* seconds. Since the seconds are not useful for many real-time scenarios, the macro tempo() was used to allow timers in microseconds:

```
#define tempo(n){
  clock_t  reveil = clock()+n;
  while(clock()<reveil) sleep(0);
}/*n in microseconds */
```

So, sleep(1) is equivalent to tempo(1000000). These timers were used in processes running in parallel and can limit the waiting time for certain events.

IV. SIMULATION SYSTEM DESCRIPTION

Two subsystems constitute the simulation system [10]:

- Grafcet entry: this subsystem offers two possibilities:
  - Graphical input: Based on a graphical editor, allows any Grafcet to be entered graphically and outputs its image data structure.
  - Text entry: Rarely used in practice, except for maintenance purposes. It allows to enter the Grafcet as text, so requires a text analyzer that outputs the same data structure as the graphical editor.
- Translation of the Grafcet: This subsystem exploits the data structure from the entry and translates it into C. Two steps are possible:
  - Interpreter/simulator: A program that executes step-by-step the appropriate C sequences according to the data structure.
  - Generator: A program that creates a complete C code of all the Grafcet. Executing this code is the simulation of the automatism described by the Grafcet, as long as this code is not configured according to real I/O.

In both cases, translation requires defining the Grafcet/C generation schemes.

V. GRAFCET/C TRANSLATION SCHEMES

The definition of the translation schemes from Grafcet to C consists of finding for each Grafcet basic element a program scheme in C which has the same semantics. The elements of Grafcet are: simple transition, divergences (AND, OR), convergences (AND, OR), the stage, and the macro stage [10].

A. Preliminary Study [10]

Let's consider the following scenario:

- A rotating bar at a position *x*, *y* of the screen successive display in *x*, *y* of characters -, /, |, \, -, /, …)
- In case of no overflows, pressing the arrow keys causes the bar to move down, left, right, and up respectively.
- If limits are exceeded, the above characters produce an audible signal, and the bar keeps rotating in the same place.
- Pressing the character "q" stops the scenario.
- Pressing any other character is ineffective.

Figure 1 shows the Grafcet of the above scenario.

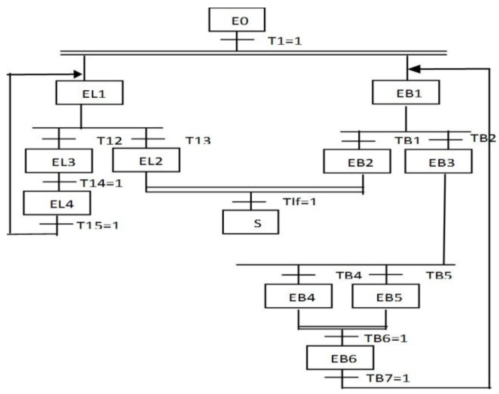


Fig. 1. Grafcet associated with the rotating bar scenario.

Let EB and TB be the stages and transitions of the rotating bar branch, and EL and TL be the stages and transitions of the reading characters branch.

Stages	E0: initial stage, beginning of the program. EB1: rotating bar. EB2: end of the rotating bar process. EB3: Test of the character read in the pipe. EB4: audible alarm. EB5: moving the bar. EB6: rest (sleep). EL1: read and test the read character. EL2: sending a KILL and exit. EL3: write ↓, ←, →, ↑ in the pipe. EL4: rest (sleep). S: end of the scenario.
Transitions	T1: pressing any key to start both processes. TB1: reception of a KILL signal. TB2: read ↓, ←, →, ↑ in the pipe. TB4: overcoming limits. TB5: no overflows. TB6: = 1; TB7 = 1 TL2: read ↓, ←, → or ↑ from the keyboard. TL3: reading of the 'q' character of the keyboard. TL4 = 1; TL5 = 1; TLF = 1.

B. Principles of the Image Program

Once the program is launched, two processes are created and launched simultaneously (proc1, proc2). Proc1 is a standalone process associated with the rotating bar, while proc2 is associated with its movement and is under external influence. At some point, the two processes must act simultaneously on the coordinates *x*, *y* of the bar. A first solution is to create a critical section within each process to achieve mutual exclusion of both accesses [8]. A second solution would be to allow effective access to a single process, such as proc1, which will rotate and move the bar, proc2 reads the arrow characters, considered as the move commands of the bar, and sends them through a pipe to proc1 to use them to move the bar in the desired direction. The end of the scenario will take place when proc2 reads the "q" key. Table I shows the general processing algorithms of proc1 and proc2. This program, modeled in Grafcet, is the basis to deduce the basic translation schemes from Grafcet into C. These schemes were extended for industrial processes where the system entries can be numerous, simultaneous, and real-time. Therefore, push buttons and sensors were integrated.

TABLE I. PARALLEL RUNNING OF PROC1 AND PROC2

Proc1	**Proc2**
At each position of the bar: Display the bar Look in p[0] if a character is placed in the pipe. If yes the character is stored in cc1 and tested. If exceeding the limits, warning sound, otherwise move in the desired direction. Rotation of the bar.	Reads a cc character from the keyboard and test it. If cc ='q' then sends a SIGKILL to proc1 then EXIT. If cc ="↓", "←", "→" or "↑" then places cc in the inlet p[1] of the pipe; If cc is other, ignore cc.

C. Grafcet-C Translation Schemes

A simple transition is an external event that can arise at any time from a sensor, button, etc. Three cases exist to simulate it: keyboard, order box, and always concurrent. Keyboard input can be given as a simple scheme:

```
cc=getch()
```

In case of an order box, let boitcom be the port address of the command box, reading 8 to 16 digital inputs. By assimilating all the bits to zero in the absence of an entry, the scheme could be the following:

```
while(!(*boitcom)) sleep(0);
```

These diagrams are taken up and developed when a configuration language would cover the essential cases concerning the real-time management of arbitrary devices, which will be part of a realistic simulation. Meanwhile, the input from the control box can be simulated by programming the keys of the keyboard, associating a sequence of bits: for i=1,…,7, command[0],…, command[7], command[i]=1 when the receptivity i is true, and command[i]=0 when no receptivity is true. In an always occurrent case, t=1, which means that the sum of the internal and external receptivity conditions is 1. In this case, a comment is generated (/* t=1 */).

1) Divergences

- AND divergence:

```
while(!t) sleep(0);
rep=forkn(tab_fonc,nproc,tab_pid);
rep1=wait(&status);
while((rep1 !=-1) wait(&status);
```

where tab_fonc is an array of pointers to functions performed in the context of each process, nproc is the number of the created processes, tab_pid is the pid chard of the created processes, and tab_fonc[i] is the pointer to the function executed by the process with the pid_tab_pid[i]. Forkn() details can be found in [9].

- OR divergence: The exclusive OR divergence is given by:

```
while(!t1&&!t2&&!t3... &&!tn)sleep(0);
switch(transition){
  case  t1 : p1();
  case  t2 : p2();
   . . .
  case  tn : pn();
}
```

where pi() is the procedure executed for the transition ti and there is no priming of new paths. Inclusive OR is given by:

```
while(!t1&& !t2&&... && !tn) sleep(0);
if(t1) p1();
if(t2) p2();
…
if(tn) pn();
/* the creative process enters the
zombie state */
rep1=wait(&status);
while (rep1 !=-1) wait(&status);
```

where pi() is the process creation procedure i. There is a boot of new paths. Two images are likely in the classical case of an input form: A general but expensive image (competition diagram), or an effective image applicable under certain conditions. In the case of an effective image, the alternative scheme is applicable if and only if the transitions are disjoined two by two.

The evaluation of this question in a generator is the subject of a decision procedure, which in case of difficulties may substitute, the absolute criterion above, one or more sufficient conditions easier to evaluate. For example, if two transitions occur as products of elementary conditions, they are disjoint if the same condition is present in the two transitions in opposite forms, such that: T1 = x y z and T2 = x y z. In the case of expectations with time-out, there is divergence with two issues, one of which carries the receptivity "event" and the other a receptivity "time limit". Since this can only be performed in excess, it is normal to consider the two as disjoint (in case of conjunction, the event is considered to have happened after the prescribed duration). The quality of the decision procedure thus directly governs the quality of the code, which may be inaccurate, correct but heavy, correct and effective, and even optimal for a perfect decision procedure. On the other hand, the generation with divergences must agree with the generation with convergences.

2) Convergences

- AND Convergence: Two cases arise: If pi has the same divergence as the origin, the synchronization is performed by wait(), while if they don't have the same origin, synchronization is mandatory. For each father process, synchro is a global variable. Initially, synchro is the number of incoming branches. Once it finishes, each process simulating an incoming branch must access synchro and decrement it. When synchro becomes null, it implies the end of all branches. As the access to synchro may be simultaneous, it must therefore be a critical section within each process, using either semaphores or locks [11]. This study used a method of choosing a process, called the coordinator, and took the one that simulates the most left incoming branch. When it finishes, the coordinator performs the following algorithm.

```
/* scheme associated with coordinator*/
/*only the coordinator accesses synchro*/
int rep ;  char cc ;
...
/* as soon as it finishes, it
decrements synchro */
synchro-- ;
while(1){
    cc = ' ';
     dup(tube1[1]);
     close(tube1[1]);
    read(tube1[0],cc,1);
    if (cc=='f') synchro--;
    ...
    cc=' ';
    dup(tuben[1]);
    close(tuben[1]);
    read(tuben[0],cc,1);
    if (cc=='f') synchro--;
}/* finwhile */
 /*  synchro=0, le process p0 kills
  all the other processes and makes
   an exit  */
      rep=kill(pid1, SIGKILL);
      rep=kill(pid2, SIGKILL);
      ...
      rep=kill(pidn, SIGKILL);
      exit();
```

Once it finishes, each other process associated with other branches should perform the following algorithm:

```
/* let's suppose the process number i,
  other than the coordinator, sends the
 character 'f' in the pipe */
 dup(tubei[0]);
 close(tubei[0]);
 write(tubei[1],'f',1);
/* infinite loop as wait */
 for( ; ;) sleep(0);
```

- OR Convergence: Exclusive OR comes down to the simple transition, while inclusive OR is discussed in the same way as the AND convergence.

3) The Stages

It executes within a process, and can be simulated by a message specifying it, possibly a time-dependent timer associated with it, encapsulated in an enn() procedure:

```
void enn()
printf("etape %d",num_etape);
tempo(duree) ;
```

4) The Macro Stage

The macro stage is translated using a procedure that is an image similar to the main program because it is a sub-Grafcet and militates a recursive generation.

5) Forcing

The diagrams can be implemented in the case where the automatism is modeled by a single Grafcet, which is a single connected component. They can be extended by adding the associated macros in the case of forcing or applied in the case of a hierarchy of Grafcets. The forcing function is an action of macro stage M. This is then called macroaction, and is a procedure using another Grafcet (slave). The functions associated with forcing operations are summarized below:

- Freezing: This operation consists of sending the signal SIGSTOP to the active stages of the given Grafcet.

```
void suspendre(g){
int i, rep ;
i=1 ;
while (i<= nbactif){
  rep=kill((pid[i],SIGSTOP);
  i++ ;
}
//nbactif = number of active stages
//pid : table of active pid
```

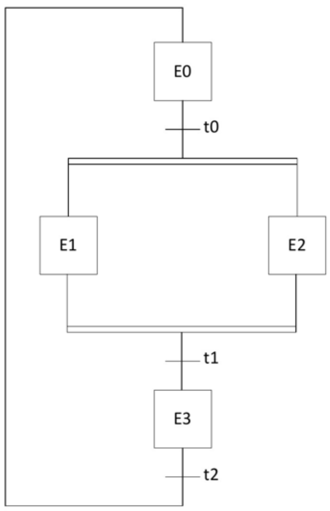
- Disabling the slave Grafcet: This operation is associated with a deactivate() procedure which consists of sending a SIGKILL signal to the active processes in the slave Grafcet given by g.
- Put in initial situation: This procedure consists of calling a subroutine that is analogous to the main program. This is similar to using the macro stage in the case of the normal operation of automation.
- Put in any situation: Two cases may arise, reactivate a previously suspended Grafcet, which would consist of sending the SIGCONT signal to the suspended process, or activate certain stages of the Grafcet in question where it would be necessary to put to true their input receptivities and launch the functions associated with them.

VI. NECESSARY CONFIGURATION FOR THE SYSTEM

The implementation of this system requires:

- A Unix or Linux or any multitasking system.
- A graphic screen for entering the Grafcet.
- A keyboard as input device and, if possible, a box of commands.
- Effectors: LEDs, bulbs, effectors.

The screen is divided into two windows. The first window (FEN1) is used to draw the currently active Grafcet (command part), while the second (FEN2) is specific to the messages that illustrate the actions carried out by the operative part. Initially, the Grafcet is animated from the initial situation. The arrival of the transitions from the keyboard or the control box causes the evolution of the Grafcet, i.e. activation of the new stage or stages (following the transition), and deactivation of the stage or stages. Active stages will be highlighted in FEN1, showing their associated messages in FEN2. The command box allows making several entries at once, a case that can be tested for OR divergences and transitions whose branches run in parallel. Figure 2 shows a Grafcet and the corresponding C program.




```
#include
grafcet.h
void
p1();
void p2();
main()
{
while (1) {
stage("E0", duration_E0);
ctransimple;
tab_fonc[0]=*p1;
tab_fonc[1]=*p2;
divet(2,tab_fonc,tab_pid);
stage("E3",duration_E3);
/*t=1*/          reinitialize(); /*
possibility of reinitializing the
automation or not by reading the
variable reinit */
if (reinit==0) break;
}
}
void p1(){
stage("E1",duration_E1);
}
```

Fig. 2. From Grafcet to C code.

VII. APPLICATION

Figures 3 and 4 show two industrial Grafcet examples that were used to validate the proposed method. The principle of validation of a Grafcet has two phases: static validation, respecting the conditions of good form, and dynamic validation of the execution.

A. Grafcet Good Form Conditions

A Grafcet is:

- Except: if for any situation accessible from E0, no step is reactivated.
- Living: If for any accessible situation from E0, a crossing sequence of any transition exists.
- Clean: If for any situation accessible for E0, there is a crossing sequence leading to E0.

B. Importance of the Preceding Properties for the Grafcet Evolution

If the Grafcet is safe, no step is reactivated during its possible evolutions. Reactivation is dangerous and can lead to errors. A living Grafcet will never block and will never find inert steps or transitions (unactivated steps, unsensitized transitions) at a certain stage of the evolution. If a Grafcet is clean, this implies possible re-initiation. This is a very important phenomenon for automation, as the initial step is considered a resting stage. The proposed method assumes:

- Transitions from the keyboard or the control box are always occurring (= 1), simulating well external or internal events.
- Simple steps: The considered Grafcet can easily be assimilated to the complete Grafcet that takes into account any type of transition or step. This method is effective for Grafcet validation.

The Grafcet shown in Figure 3 is not safe because there is a reactivation of step 2, in the case of crossing transition 5. The proposed method indicates it by a message and rejects it when meeting again step 2 within the normal operating cycle.

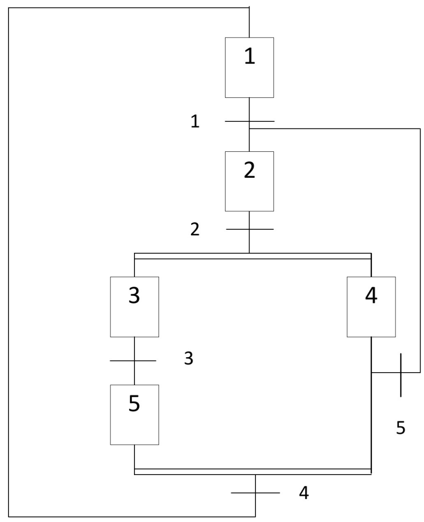


Fig. 3. Industrial Grafcet example1.

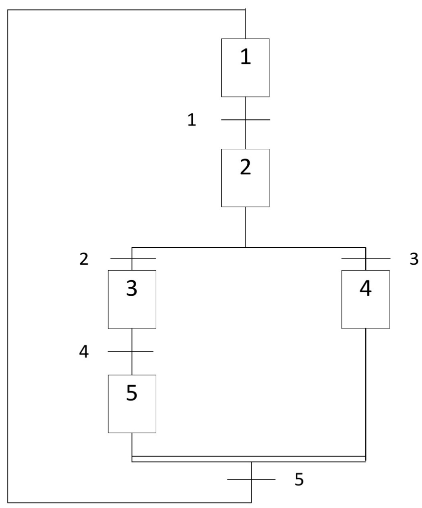


Fig. 4. Industrial Grafcet example2.

In Figure 4, transitions 2 and 3, are OR divergences. If they occur together, the OR of this divergence is inclusive and the Grafcet is clean, alive, and safe. If they do not occur together, the OR is exclusive, and one branch will be executed, but arriving at the AND convergence, transition 5 can be crossed only if steps 4 and 5 are both active and the transition is equal to 1, which is not the case if the OR is exclusive. The proposed program reports a blockage in this case.

C. Compatibility of Simultaneous Actions and Correlation of Stages and Receptivity

A subsystem displaying the steps and associated actions would allow the user to know if the steps that have run simultaneously correspond to compatible actions, after observing the execution of the Grafcet. For example, two pumps, one operating while the other is at rest, should never appear together in two simultaneous actions in a Grafcet. Similarly, the action-receptivity correlation can be checked by consulting the transitions and the associated receptivity conditions (the symbol table contains all the information relating to the steps and transitions).

D. Search of Cycles

In principle, a cycle exists, outside the normal operating cycle, if there is a reactivation of at least one previous step. The proposed algorithm, as designed, rejects the Grafcet as soon as a previously activated stage is reactivated. A cycle within the normal cycle of operation can have dangerous consequences.

VIII. CONCLUSION

The proposed algorithm allows to translate a large number of Grafcets by compositions of the most elementary elements. On a practical level, this study created a Grafcet library of translation diagrams. This library was tested on several examples, is independent of the assumed internal form, takes into account the automatisms described by a single Grafcet, and can be extended to explicit macros and procedures relating to forcing processing used in the case of a Grafcets hierarchy. A program was developed that requires to start from a graphic editor or specialized analyzers to enter the Grafcet in an internal form to produce a C code whose execution will behave according to the entered Grafcet. Automatic production of the C code is based on the elementary translation schemes described. As a second step, after the test, validation, and configuration of the algorithm and the program, the object code can be implemented on the microcontroller of the actual control system, in particular explaining everything related to the execution configuration. The advantage of the proposed algorithm is that it can be widely used because it requires a simple hardware and software configuration as a microcomputer equipped with the Linux operating system is more than enough. Compared to other works, the proposed method can simulate any type of Grafcet and the various forcing treatments, and it presents precision and exhaustiveness. The only downside of the proposed method is that Unix is not quite real-time, but this approach can be assumed as complete by staying at the simulation stage. Future work would focus on translating Grafcet into Promela/SPIN.

ACKNOWLEDGMENT

This paper pays tribute to Mr. Louis Frécon, who was a professor at INSA/Lyon, and passed away on November 11, 2018, for his contribution during the realization of this work.

REFERENCES

[1] O. A. Adebimpe, V. Oladokun, and O. E. Charles-Owaba, "Preventive Maintenance Interval Prediction: a Spare Parts Inventory Cost and Lost Earning Based Model," *Engineering, Technology & Applied Science Research*, vol. 5, no. 3, pp. 811–817, Jun. 2015, https://doi.org/10.48084/etasr.565.

[2] L. S. Tavassoli, N. Sakhavand, and S. S. Fazeli, "Integrated Preventive Maintenance Scheduling Model with Redundancy for Cutting Tools on a Single Machine," *Engineering, Technology & Applied Science Research*, vol. 10, no. 6, pp. 6542–6548, Dec. 2020, https://doi.org/10.48084/etasr.3903.

[3] M. A. Munir, M. A. Zaheer, M. Haider, M. Z. Rafique, M. A. Rasool, and M. S. Amjad, "Problems and Barriers Affecting Total Productive Maintenance Implementation," *Engineering, Technology & Applied Science Research*, vol. 9, no. 5, pp. 4818–4823, Oct. 2019, https://doi.org/10.48084/etasr.3082.

[4] B. M, *Comprendre Maîtriser Et Appliquer Le Grafcet*. Toulouse, France: Éditions Cépaduès, 2005.

[5] Reeb Bernard, Développement des grafcets : des machines simples aux cellules flexibles, du cahier des charges à la programmation / Bernard Reeb, Nouvelle édition. Paris, France: Ellipses, 2011.

[6] Z.Remaki, J. F. Ponsignon, M. Nekkache, "Schémas de traduction grafcet Occam2", presented at the 3rd Maghreb Congress on Artificial Intelligence and Software Engineering, Rabat, Morocco, 1994.

[7] E. González, R. Marichal, and A. Hamilton, "Ontology-based approach to Basic Grafcet formalization," *Journal of the Chinese Institute of Engineers*, vol. 39, no. 8, pp. 946–953, Nov. 2016, https://doi.org/10.1080/02533839.2016.1215939.

[8] O. Miguel-Escrig, J.-A. Romero-Pérez, B. Wiesmayr, and A. Zoitl, "Distributed implementation of Grafcets through IEC 61499," in *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, Vienna, Austria, Sep. 2020, vol. 1, pp. 402–409, https://doi.org/10.1109/ETFA46521.2020.9212087.

[9] W. Stevens and S. Rago, *Advanced Programming in the UNIX Environment, 3rd Edition*, 3rd edition. Upper Saddle River, New Jersey: Addison-Wesley Professional, 2013.

[10] Nacéra Benaouda and Abdelhafid Benaouda, "Translating Grafcet Specifications into C/Unix Program," presented at the IADIS International Conference Information Systems 2021, 2021, pp. 209–217.

[11] M. Raynal, Concurrent Programming: Algorithms, Principles, and Foundations. Springer, 2013.