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Authenticating topological integrity of process plant models through digital watermarking

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Abstract Process plant models, which feature their intrinsical complex topological relation, are important industrial art works in the field of Computer-Aided Design (CAD). This paper investigates the topology authentication problem for process plant models. Compared with the widely studied watermarking based geometrical information protection and authentication techniques for traditional mechanical CAD drawings, topology authentication is still in its infancy and offers very interesting potentials for improvements. A semi-fragile watermarking based algorithm is proposed to address this interesting issue in this paper. We encode the topological relation among joint plant components into the watermark bits based on the hamming code. A subset of the model's connection points are selected as mark points for watermark embedding. Then those topology sensitive watermark bits are embedded into

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selected mark points via bit substitution. Theoretical analysis and experimental results demonstrate that our approach yields a strong ability in detecting and locating malicious topology attacks while achieves robustness against various non-malicious attacks.

Keywords Watermarking · Semi-fragile watermarking · Topology authentication · Topological integrity · Process plant model · Connection points

1 Introduction

The Computer-Aided Plant Design system is now increasingly used in process industries for helping increase productivity and collaboration to meet the challenges of complex plant design projects. Collaborative design is the process where multidisciplinary designers participate in designing decision-making and share product information across enterprize boundaries. During the collaboration, a manufacturer may share process plant models, as one kind of 3D Computer-Aided Design (CAD) models, with its supplier as design specifications. They may also share process plant models with their customers for analysis and simulation purposes. Therefore, particular attention to integrity authentication is necessary for process plant models in the collaborative environment.

The complex topological relation is one of the most important items to be authenticated in process plant models. Various construction documents, such as isometrics, orthographics, etc., are automatically generated from the process plant model on the basis of complex topological relation among joint plant components. The problem of topology authentication for process plant models can be classified into joint plant components authentication and joint ends authentication. For each plant component, joint plant components authentication first verifies whether its joint plant components are changed. Furthermore, for each of its ends, joint ends authentication identifies whether its joint ends are modified.

Digital watermarking provides an effective and reasonable solution for the integrity authentication of multimedia objects [23]. It has been widely studied for authenticating multimedia objects including sound [20], still image [2], video [14], three-dimensional(3D) models [24, 5, 13], etc. Process plant models, as one kind of 3D CAD models, can also be regarded as a full-fledged multimedia data type, although this may not be a common perception [16]. However, relatively few watermarking algorithms have been proposed for 3D CAD models especially process plant models. Furthermore, the geometrical information has been the focus of the research in watermarking CAD models including CAD-based drawings, parameterized curves and surfaces, etc. For CAD-based drawings, Peng et al. proposed two watermarking schemes for 2D CAD engineering graphics by modifying coordinates of vertices based on improved difference expansion and log-polar transformation respectively [18, 19]. Lee et al. presented a robust watermarking scheme based on geometric features

with k-means++ clustering for 3D CAD drawings [12]. Kwon et al. described two algorithms for 3D CAD drawings by selecting LINE, FACE, and ARC components as watermark carriers [8, 7]. For parameterized curves and surfaces, Ohbuchi et al. presented a watermarking scheme for 3D NURBS curves using reparameterization [17]. Lee et al. proposed a method for watermarking NURBS data using two-dimensional virtual images [11]. A robust non-blind watermarking scheme for subdivision surfaces was presented by Lavoué [10]. Kwon et al. presented a blind watermarking scheme for rational Bézier and B-spline curves and surfaces [9]. In summary, existing watermarking schemes for CAD models mainly target the geometrical information protection or authentication. Topology authentication for process plant models is still in its infancy and offers very interesting potentials for improvements.

In this paper, we dedicate to tackle the problem of topology authentication for process plant models. The first contribution of this paper is the design of a novel semi-fragile watermarking based scheme for the topology authentication problem. It is a novel application of the watermarking technique on the topology integrity verification for process plant models. This idea is inspired by existing fragile or semi-fragile watermarking schemes for authenticating the integrity of various multimedia objects. The semi-fragile technique proposed in this paper is vulnerable to even very slight modifications of the topological relation among plant components. Furthermore, it is also capable of locating and identifying the attacked regions accurately. The second contribution of the paper is that we encode the topological relation into the singular watermark bits for each mark connection point. Thus, any attack which ruins the topological relation will result in the modification of extracted watermark bits.

The remainder of the paper is organized as follows. We give a brief introduction of the topological relation of process plant models and review some related techniques in Section 2. After that, we describe in detail the procedure of embedding and extracting watermark bits in Section 4. Section 5 demonstrates and discusses the experimental results. Conclusion and future work follow in Section 6.

2 Preliminaries

2.1 Topological modeling of Process plant models

The process plant model covers three kinds of information: geometrical information, engineering information, and topological information. Geometrical information describes the shape and 3D positions. Engineering information refers to design constraints, engineering disciplines and so on. Topological information provides the complex topological relation among joint plant components. We give a detailed introduction of the topological relation representation among various joint plant components in this section.

Process plant models feature their intrinsical complex topological relation rather than geometrical shape represented by various basic solid entities, such

as box, cylinder, prism, and sphere. Topological modeling concerns with the most economical spatial arrangement of process vessels, equipments and their interconnections that satisfy construction, operation, maintenance, and safety requirements. And it poses significant limitations on the type, size and location of plant components. Not only should the layout represent the interconnection among joint plant components, but it should also describe their exact interconnection ends. Only the two ends of two joint plant components which satisfy the specific requirements, such as pipe diameter, end type, pressure rating, and flow direction, can then be connected.

There are mainly two popular ways, which are widely used in many commercial process plant design softwares, to represent the end connection. One is connection points [3], the other is the order of plant components stored in the file. This paper aims to watermark process plant models which describe the end connection by virtue of connection points. Connection points are, in fact, point entities. They are normally defined as the center points of end faces. In Computer-Aided Plant Design systems, connection points are added, deleted and transformed along with their corresponding plant components. And the maintenance of connection points is carried out automatically by Computer-Aided Plant Design systems without the need of human intervention.

The core structure of the connection point consists of geometrical information, topological constraint, handle value and various engineering properties, which are shown in Fig. 1. The geometrical information indicates its actual location. Topological constraint covers its joint connection point and the corresponding plant component it subjects to. Each connection point may have one joint connection point at most. The handle value is an abstract reference to an entity in the process plant model. It (i.e., an identification number) is unique and is not altered even if the entity is modified (i.e., translated, rotated and scaled)[18]. This intrinsic invariance property is employed to generate watermark bits. Fig. 2 shows connection points of a simple pipeline. Take the connection point $P_{i,1}$ for example, its corresponding plant component is C_i and $P_{i+1,0}$ is its joint connection point.

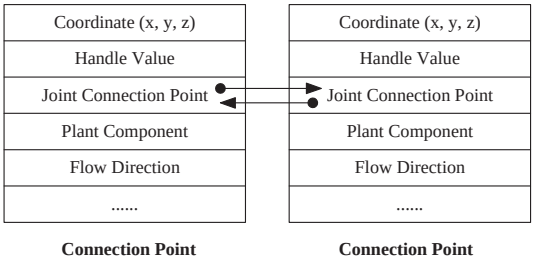


Fig. 1 The core structure of connection points

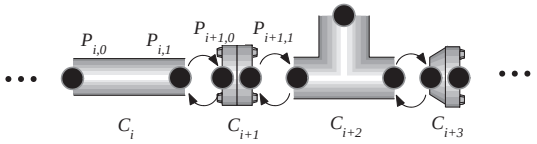


Fig. 2 An example of connection points of a simple pipeline. Note that all the connection points are scaled for better illustration

2.2 Logistic map

The topological relation among joint plant components is involved in the watermark generation using the deterministic logistic map in this paper. Logistic map is a chaotic map that can generate chaotic signal which has the extreme sensitivity to initial conditions, randomness and uniform distribution [15]. Due to these characteristics, it has been widely used for watermarking and encryption [15, 1]. The function used in this paper is defined as:

$$x_{n+1} = ax_n(1 - x_n), \tag{1}$$

where a is the control parameter and x_n is the current value of the mapping in time with an initial value x_0. The sequence iterated with an initial value is chaotic when $3.5699456 < a \leq 4$. And different sequences will be generated with different initial values.

2.3 Hamming code

The hamming code, first proposed by R.W. Hamming[6], is employed both in the watermark generation and extraction stage of our scheme. Parity check is the basic idea of the Hamming code. The hamming code detects errors by ensuring that each parity check bit and its corresponding data bits achieve the goal of even parity. In this paper, we utilize the hamming code $(15, 11)$ for generating the content-based watermark bits as well as detecting the tampered plant components and connection points.

3 Overview of the algorithm

Our topology authentication scheme consists of two parts: watermark embedding part and watermark extracting part. Fig. 3 shows the overview of our scheme. In the following parts, we call the connection points to be watermarked as mark connection points and the other points as non-mark connection points.

In the watermark embedding part, we first select mark plant components and mark connection points from the model following the mark connection points selecting principle. Then, the topological relation among joint plant components is employed to generate singular content-based watermark bits for each mark connection point. After that, we embed the topology sensitive

watermark bits into each mark connection point by modifying its coordinate according to the watermarks embedding method. Finally, we generate the watermarked model.

In the watermark extracting part, the scheme first finds out all mark plant components and mark connection points. Then, the tamper detection method is applied to detect and locate the tampered regions and report them visually. In order to identify mark connection points and mark plant components, we extract the watermark bits for each connection point according to the watermarks extraction method. Meanwhile, we compute the content-based watermark bits for each connection point through the content-based watermark generation method. After that, the extracted and generated watermark bits are used to identify mark connection points and mark components.

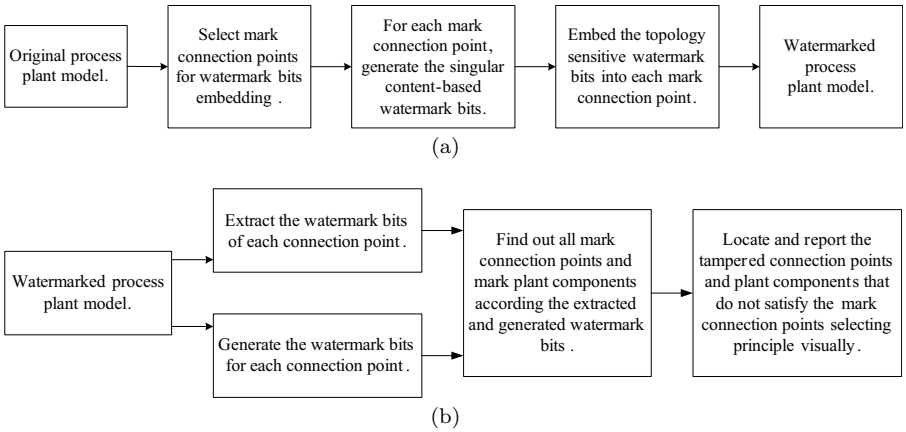


Fig. 3 Overview of our semi-fragile watermarking scheme for topology authentication and verification. (a)Watermark bits embedding; (b)Watermark bits extraction

4 Watermarking based topology authentication

In this section, we discuss our watermarking scheme for topology authentication. We first select a proper portion of connection points from the model for embedding watermark bits. After that, we generate content-based watermark bits for each mark connection point. At the end of this section, we describe in detail the procedure of embedding and extracting watermark bits.

4.1 Mark connection points selecting principle

Connection points, rather than geometrical parameters of plant components, are preferred as watermarking targets in this paper. Thus, the geometrical

shape of the model would not be influenced by the watermark embedding. The principle of mark connection points selecting is described as follows.

First, we select all mark plant components from the model. Initially, all plant components are set as non-mark components. We traverse each pipeline of the model according to the flow direction and get eligible plant components for watermark embedding according to the discipline below.

- One and only one of the two joint plant components must be selected as a mark plant component.
- For a selected mark plant component, its 1-ring neighboring components are no longer eligible.

After the selecting of mark plant components, we set all their connection points as mark connection points for watermark embedding. Fig. 4 illustrates the mark plant components selection of a simple pipeline. From Fig. 4, we can see that the union of selected mark plant components and their 1-ring neighborhood cover all plant components of the model. Therefore, it can be guaranteed that the mark plant components and their mark connection points are uniformly distributed in the model. And this can result in high locating accuracy.

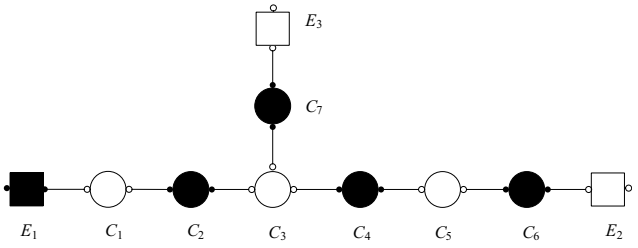


Fig. 4 Illustration of mark plant components selection.Circular nodes represent pipe components while rectangular nodes represent equipments. Black nodes are selected mark plant components while white nodes are non-mark plant components

4.2 Content-based watermark generation

We generate singular content-based watermark bits for each mark connection point based on the hamming code $(15, 11)$ and the logistic map method. Handle values of connection points and their corresponding plant components are all involved in the watermark generation.

Assume that a mark plant component C_i with n_i^p mark connection points is connected with a non-mark plant component C_{i+1} with n_{i+1}^p non-mark connection points. Without loss of generality, let $P_{i,j}$ $(j \in [0, n_i^p - 1])$ be a mark connection point of C_i and its joint connection point be $P_{i+1,k}$ $(P_{i+1,k} \in C_{i+1}, k \in [0, n_{i+1}^p - 1])$. Denote the handle values of C_i, C_{i+1}, $P_{i,j}$ and $P_{i+1,k}$

as H_i^c, H_{i+1}^c, $H_{i,j}^p$ and $H_{i+1,k}^p$ respectively. The watermark generation method is described as follows.

1) First, the handle values of the two joint connection points $P_{i,j}$ and $P_{i+1,k}$ are converted into two positive float numbers $F_{i,j}$ and $F_{i+1,k}$ respectively by
$$\begin{cases} F_{i,j} = hash(H_{i,j}^p), \\ F_{i+1,k} = hash(H_{i+1,k}^p), \end{cases} \tag{2}$$
where $hash()$ is a hash function, $0 < F_{i,j} < 1$ and $0 < F_{i+1,k} < 1$.
2) Then, $F_{i,j}$ and $F_{i+1,k}$ are used as initial values of the logistic function shown in (1). And we perform the logistic function with the two initial values to obtain two float values $L_{i,j}$ and $L_{i+1,k}$ respectively.
3) After that, we select 11 bits each from the mantissa parts of both $L_{i,j}$ and $L_{i+1,k}$ under the control of the private key H_i^c and H_{i+1}^c respectively.
4) Let two selected bits be $Bits_{i,j}$ and $Bits_{i+1,k}$ respectively. Then a bitwise XOR operation between the picked mantissa $Bits_{i,j}$ and $Bits_{i+1,k}$ is performed. Finally, four parity check bits, also called the watermark bits $w_{i,j}$, are generated for $P_{i,j}$ from the produced 11 bits data, namely $X_{i,j}$, by the (15,11) hamming code.

It is worth mentioning that there may be some mark connection points with no joint connection points. Given that $P_{i,j}$ is a mark connection point of C_i and it has no joint connection point. Its watermark bits are generated as follows.

1) First, we convert the handel value of the mark connection points $P_{i,j}$ into a positive float number $F_{i,j}$ by
$$F_{i,j} = hash(H_{i,j}^p), \tag{3}$$
where $hash()$ is a hash function, $0 < F_{i,j} < 1$.
2) Then, the logistic function shown in (1) is performed with the initial value $F_{i,j}$ and consequently a float value $L_{i,j}$ is generated.
3) After that, we select 11 bits, denoted as $Bits_{i,j}$, from the mantissa parts of $L_{i,j}$ under the control of the private key H_i^c. Finally, four parity check bits are generated as watermark bits $w_{i,j}$ for $P_{i,j}$ from the produced 11 bits data $Bits_{i,j}$ by the (15,11) hamming code.

Fig. 5 gives an example of how to generate the watermark bits for a mark connection point. These content-based watermark bits are then embedded into mark connection points for topology authentication.

4.3 Watermarks embedding and extraction method

4.3.1 Watermarks embedding

The watermarks embedding method is used to embed the topology sensitive watermark bits into each mark connection point for topology authentication

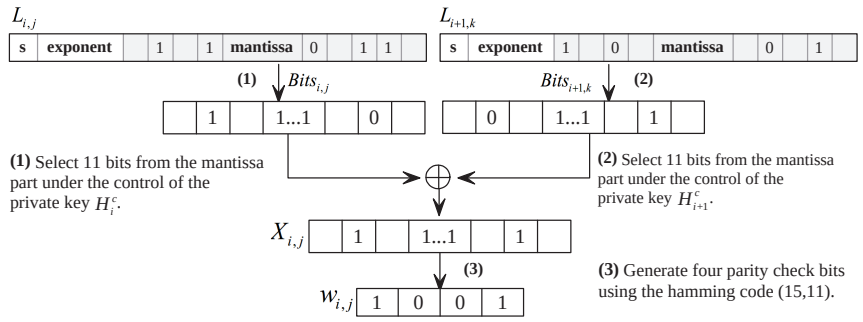


Fig. 5 The example illustrates how the four parity check bits are generated. Data are in the IEEE-754 float32 format

and verification. Provided that $P_{i,j}$ is a mark connection point to be watermarked. Its joint plant component is C_{i+1} with n_{i+1}^p non-mark connection points. Let the total number of joint plant components of C_{i+1} be n_{i+1}^c, which is used as a private key for the watermark embedding. The watermark embedding scheme is presented as follows:

1) We first find the sets of neighboring connection points $S(P_{i,j})$ of $P_{i,j}$. $S(P_{i,j})$ is defined as the sets of $P_{i,j}$ and all the connection points $P_{i+1,k}$ of C_{i+1}.

$$S(P_{i,j}) = \{P_{i,j}\} \bigcup \{P_{i+1,k} | P_{i+1,k} \in C_{i+1}, 0 \leq k \leq (n_{i+1}^p - 1])\} \quad (4)$$

2) Then the PCA based transformation [4] is applied to the sets of connection points $S(P_{i,j})$. After that, we convert the transformed point sets to spherical coordinates. Thus, $P_{i,j}$ is represented as $(r_{i,j}, \theta_{i,j}, \varphi_{i,j})$. This is done in order to achieve robustness against uniform scaling by embedding the watermark bits into the $r_{i,j}$ component of each connection point.
3) For the $r_{i,j}$ component, we select four bits from the mantissa parts of $r_{i,j}$ under the control of the private key n_{i+1}^p, and substitute them with the four watermark bits $w_{i,j}$ generated for $P_{i,j}$.

The watermark embedding process is performed for each mark connection point and finally the watermarked process plant model is archived.

4.3.2 Watermarks extracting

We now discuss how to extract the watermark bits for each connection point. Let C_i be a plant component with n_i^p connection points and n_i^c joint plant components. For each connection point $P_{i,j}$ of C_i, we perform the following parts to extract the watermark bits.

1) First, we find the sets of neighboring connection points $S(P_{i,j})$ of $P_{i,j}$.

2) Then, we apply the PCA based transformation to the point sets $S(P_{i,j})$. After that, we convert the transformed point sets to spherical coordinates to get the similarity transformation invariant variable $r_{i,j}$ of $P_{i,j}$.
3) Finally, four bits strings $w'_{i,j}$ are taken from the mantissa parts of $r_{i,j}$ as extracted watermark bits under the control of the private key n_i^c.

4.4 Tamper detection

This procedure is used to detect and locate the tampered plant components and connection ends accurately. Given a watermarked process plant model, we initially set all plant components and their connection points as non-mark plant components and non-mark connection points respectively. The tamper detection and locating procedure are described as follows.

First, we check and find out all of the mark plant components. Let C_i be a plant component with n_i^p connection points.

1) For each connection point $P_{i,j}$ of C_i, we first extract the watermark bits $w'_{i,j}$.
2) Then, we compute the watermark bits $w_{i,j}$ for $P_{i,j}$ according to the content-based watermark generation method described in Section 4.2.
3) After that, the watermark bits $w_{i,j}$ is compared with the extracted watermark bits $w'_{i,j}$. $P_{i,j}$ is a mark connection point if $w_{i,j}$ is identical to $w'_{i,j}$. We label C_i as a mark plant component if it has at least one mark connection point. Otherwise, C_i is set to be a non-mark plant component.

After the labeling of mark plant components and their mark connection points, we detect and locate the tampered regions following the mark connection points selecting principle.

1) For each pipeline, we traverse its plant components according to its flow direction and check if the labeled mark plant components satisfy the mark connection points selecting principle. We set those plant components which do not meet the mark connection points selecting principle as tampered plant components.
2) For each mark plant component, we set it as an unmodified plant component only if all of its connection points are identified as mark connection points. Otherwise, we label its non-mark connection points and their joint plant components as suspicious regions.

5 Performance discussion and experimental results

In this section, we discuss the performance of our semi-fragile watermarking scheme on detecting and locating various attacks.

We conduct some experiments on a number of process plant models and three of them are shown in Fig. 6. We give the numbers of plant components

and connection points of each model in Table 1. Plant components are principle geometrical components of process plant models. Connection points are employed to represent the complex topology relation among various joint plant components. The numbers of mark plant components and mark connection points, which are selected for watermark bits embedding, are also listed.

The logistic function shown in (1) was seeded with a value $a = 4$. It is observed that, for values of $3.5699456 < a \leq 4$, x_{n+1} distributes more uniformly over the whole interval $[0, 1]$ as $n \to \infty$ when a is closer to 4 [15]. To enhance the security of our algorithm, the number of iterations n is set to be 3000 on the premise of computation efficiency since large iterations witnesses the chaotic behavior significantly.

(a) (b) (c)

Fig. 6 Three of our tested process plant models. (a)Carton board plant; (b)Hydrogenation plant; (c)Styrene plant

Table 1 Detail information about three of our tested process plant models. The numbers of plant components(PCs), connection points(CPs), mark plant components(MPCs) and mark connection points(MCPs) of these models are listed respectively.

Model	PCs	CPs	MPCs	MCPs
Carton board	6810	13964	3365	7002
Hydrogenation	15570	32624	8145	16556
Styrene	18912	38198	9652	19484

5.1 Tamper detection and localization

In this section, we analyze and evaluate the performance of our scheme on detecting and locating the tampered regions on the model. The attacks mentioned in this section include components modification and joint ends modification, which are common operations provided by Computer-Aided Plant Design systems.

5.1.1 Components modification

Topological attacks against plant components mainly cover adding and deleting components.

For plant components adding, there exist two main situations about the joint plant component of the newly added one: non-mark plant component and mark plant component.

- If the newly added plant component is connected with an existing non-mark plant component, it will be labeled as a non-mark plant component during the tamper detection stage. That's because no watermark bits are embedded in its connection points. And this will lead to the mismatch between the extracted and generated watermark bits. Therefore, the two joint plant components are all non-mark plant components. Consequently, they will be set as tampered plant components since they do not satisfy the mark connection points selecting principle.
- Assume that the newly added plant component C_m is connected with an existing mark plant component C_i. And their two joint connection points are $P_{m,k}$ and $P_{i,j}$ respectively. This kind of attacks changes the topological relation of the mark connection point $P_{i,j}$. Therefore, the extracted watermark bits of $P_{i,j}$ during the watermark extraction stage are different from the watermark bits computed according to the content-based watermark generation method. As a result, the previous mark connection point $P_{i,j}$ will be labeled as a non-mark connection point. And then it, together with the newly added plant component, is set to be tampered.

For plant components deletion, two situations arise: non-mark components deletion and mark component deletion.

- Provided that the non-mark plant component C_{i+1} to be deleted is connected with its joint plant component C_i through their connection points $P_{i+1,k}$ and $P_{i,j}$ respectively. In this case, C_i is a mark plant component and $P_{i,j}$ is one of its mark connection points. There will be no joint connection point for $P_{i,j}$ if the non-mark plant component C_{i+1} is deleted from the model. As a result, the extracted watermark bits of $P_{i,j}$ during the watermark extraction stage are different from the watermark bits computed according to the *content-based watermark generation method*. Thus, the connection point $P_{i,j}$ of the mark component C_i is labeled as a non-mark connection point. Therefore, it is set as a tampered connection point.
- Given that the deleted mark plant component is C_i, which is shown in Fig. 7. This kind of attacks reduces the total number of joint plant components of the non-mark plant component C_{i-1} which is connected with the deleted one. For example, the total number of joint plant components n_i^c of C_i is reduced from 2 to 1 due to the deletion of C_{i+} in Fig. 7. As described in Section 4.3, n_i^c is employed as a key value for both watermark embedding and extraction. Consequently, the modification of n_i^c will lead to the mismatch between the embedded watermark bits and the extracted watermark bits of the mark connection point $P_{i-2,1}$. As a result, the mark

connection point $P_{i-2,1}$ and its joint plant component C_{i-1} are labeled as tampered regions.

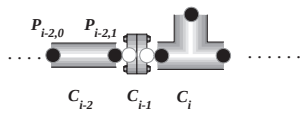


Fig. 7 Illustration of detecting and localizing mark plant components deletion attacks. C_{i-1} is a non-mark plant component. C_{i-2} and C_i are mark plant components. Black points represent mark connection points while white points represent non-mark connection points

Fig. 8 illustrates that our scheme accurately detects and locates the components modification attacks. Fig. 8 (b) and Fig. 8 (c) have been attacked by adding components and deleting components respectively. These regions are labeled as 'A' and 'B' respectively. From Fig. 8 (b) and Fig. 8 (c) we can find that the regions in red are exactly where the tampered operations happen. The experimental results verify the accuracy of our locating procedure.

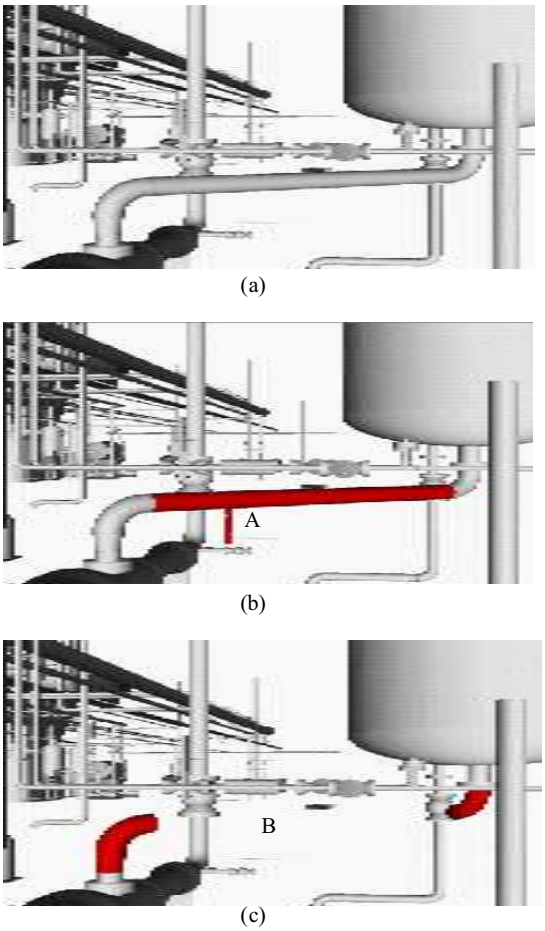
5.1.2 Joint ends modification

As discussed above, one of the two joint connection points should be a mark connection point. Given that the mark connection point is P while its joint non-mark connection point is $P^{'}$. The joint connection point of P will be altered if the topological relation between P and $P^{'}$ is modified. Thus, during the watermark extraction stage, the extracted watermark bits will be different from the embedded ones, which are initially generated according to the topological relation between P and $P^{'}$. Consequently, the two joint connection points and plant components are set as tampered regions.

Fig. 9 illustrates that our scheme accurately detects and locates the joint ends modification attacks. Fig. 9 (b) and Fig. 9 (c) have been attacked by disconnecting the two joint ends geometrically and logically respectively. These regions are labeled as 'A' and 'B' respectively. From Fig. 9 (b) and Fig. 9 (c) we can find that the regions in red are exactly where the tampered operations happen. The experimental results verify the accuracy of our locating procedure.

5.2 Robustness against non-malicious attacks

To evaluate the robustness of our algorithm against various operations provided by Computer-Aided Plant Design systems which can be considered to be non-malicious attacks, we take the watermarked model and apply a combination of rotation, uniform scaling and translation. In our experiment, attack



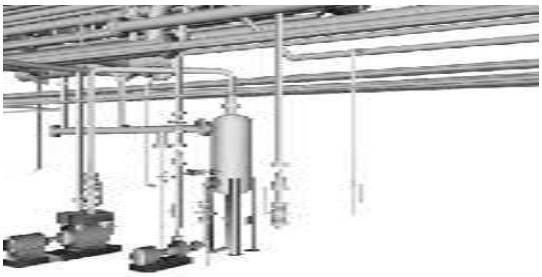
(a) (b) (c)

Fig. 8 One example of components modification attacks detecting and locating using our scheme

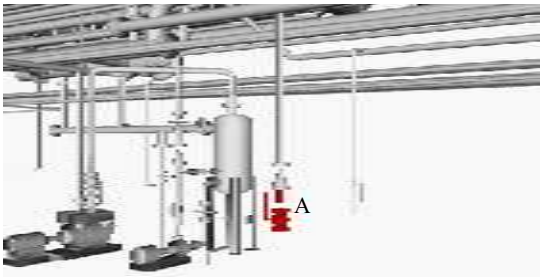
types are classified as similarity transformation attacks (i.e. translation, rotation, and uniform scaling) and simplification attack. For the robustness, we employ Bit Error Rate (BER) to evaluate the difference between the embedded and extracted watermark bits.

5.2.1 Robustness against similarity transformation

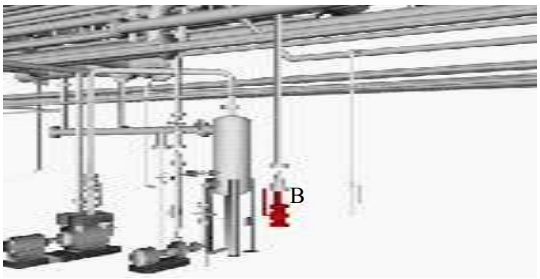
Due to the invariance properties of the PCA based transformation that is applied to the model prior to watermark embedding and detection [4], the results for similarity transformation attacks are identical to the ones produced when no attack is performed. Furthermore, similarity transformations do not destroy the topology relation among joint plant components. Therefore, the



(a)



(b)



(c)

Fig. 9 An example of joint ends modification attacks detection using our scheme

Table 2 BER of the extracted watermark bits in various attacks

Attacks	Carton board	Hydrogenation	Styrene
RST			
Rotation	0	0	0
Uniform scaling	0	0	0
Translation	0	0	0
LOD			
(90% triangles)	0	0	0
(60% triangles)	0	0	0
(30% triangles)	0	0	0

watermark bits can be extracted without a bit error in spite of the translation, rotation, and uniform scaling.

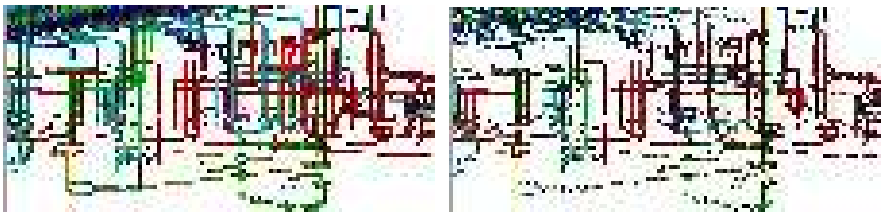
Table 2 presents the robustness evaluation results in terms of the BER under the similarity transformation. The tested models are rotated by arbitrary angles, scaled by an arbitrary ratio uniformly, and translated to an arbitrary position. As seen from the BER values listed in Table 2, our scheme is robust against translation, rotation, and uniform scaling.

5.2.2 Robustness against simplification

Computer-Aided Plant Design systems regularly generate complex models that exceed the interactive visualization capabilities of current graphics systems. The enormous size of process plant models poses a number of challenges in terms of interactive display and manipulation. Several acceleration techniques that reduce the number of rendered polygons have been proposed. Levels of detail (LOD) is one of the key techniques to reduce the model complexity and improve the rendering performance for large scale complex models. It precomputes different LODs of a given model. At runtime, before rendering each frame, the appropriate LODs to display are selected so that coarser approximations are used for models that are further away or contribute less to the final image.

In this paper, we prefer the connection points rather than the geometrical parameters of plant components as embedding targets. Thus, our embedding method has no influence on the geometrical shape of process plant models and vice versa since LOD can only change the details of entity surfaces. The set of connection points and topological relation among plant components will not be affected. Therefore, our scheme is robust against LOD.

The robustness evaluation results against simplification are also showed in Table 2. We generate three simplified models with different levels for each tested model. Fig. 10 shows a part of a watermarked model rendered with different precisions. From both Table 2 and Fig. 10 we can conclude that our scheme is invariant to LOD.



(a) (b)

Fig. 10 A part of a watermarked model with different precisions. The model is rendered in the wire-frame mode.

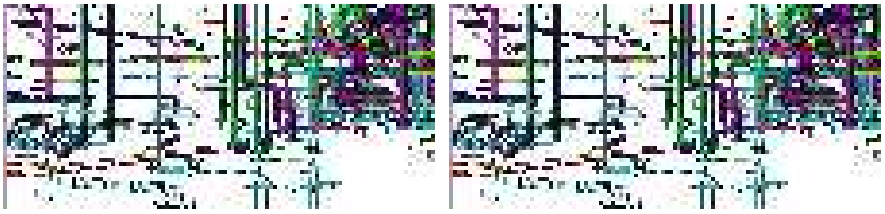
5.3 Imperceptibility evaluation

As discussed in Section 5.2.2, our scheme has no influence on the geometrical shape of plant components. Nevertheless, we still give an objective measure for evaluating the quality of a process plant model. The root mean square error (RMSE), as formulated in (5), is used to measure the distortion inflicted on the connection points by our watermarking scheme.

$$RMSE = \frac{1}{n}\|P - P^{'}\|, \tag{5}$$

where P and $P^{'}$ are the sets of connection points in the process plant model and its watermarked counterpart, respectively, and n is the number of connection points. It should point out that the geometrical shape of plant components are independent of their connection points.

Table 3 details the RMSEs of connection points of the three tested models. From Table 3 we can see that the geometrical distortion of connection points between the original model and the watermarked model is very small. Fig. 11 also shows a close view of a part of the original and watermarked models. Since only the position of each mark connection point is modified by the watermark embedding, our scheme does not alert the topological relation of the process plant model. Therefore, our scheme is visually and functionally imperceptible.



(a) (b)

Fig. 11 A close view of a part of the original and watermarked models rendered in the wire-frame mode.(a) The original model. (b) The watermarked model.

Table 3 The RMSE values of connection points of each tested model. The number of connection points (CPs) and mark connection points (MCPs) of each model are also listed

Model	CPs	MCPs	RMSE($\times 10^{-4}$)
Carton board	13964	7002	0.237
Hydrogenation	32624	16556	0.512
Styrene	38198	19484	0.403

5.4 Discussion of watermarking targets

Connection points, rather than geometrical parameters of plant components, are selected as watermark carriers in our scheme due to the following reasons.

- First of all, as described in Section 2.1, the topological relation among plant components is represented through connection points. Any malicious attack against topological relation will inevitably give rise to the modification of corresponding connection points.
- Second, geometrical parameters of plant components are employed to support the automatic generation of various construction documents. The modification of geometrical parameters will certainly result in incorrect construction documents. On the contrary, no geometrical and topological information of plant components will be induced by slight coordinates modification of connection points.

Therefore, we conclude that connection points are the best candidates for watermark embedding.

Both theoretical analysis and experimental results discussed above demonstrate that our scheme can resist to various operations provided by Computer-Aided Plant Design systems which may be seen as malicious or non-malicious attacks. However, in theory, one may still change the components while deliberately keep the connection points unchanged through various possible means. For example, an existing component may be deleted or replaced with a new component of the same type while its connection points are deliberately kept unchanged. In that case, the geometrical information of those connection points is kept the same. But the topology constraint is modified since the corresponding plant components they subject to are changed. As discussed above, this kind of attacks can still be detected and located by our scheme.

5.5 Comparison with previous works

Digital watermarking schemes have been widely studied for traditional mechanical CAD drawings. However, topology authentication of process plant models is still in its infancy and offers very interesting potentials for improvements. In this section, we compare the proposed method with previous related works.

In order to solve the problem of topology authentication for process plant models, an effective semi-fragile watermarking method based on Laplacian coordinates and quantization index modulation was proposed in [22]. However, the proposed scheme required a pre-computed mapping table for watermark extraction and tamper detection. And the table should be reserved for each distributed process plant model. This introduces a level of inconvenience to the practical application. We also present a semi-fragile watermarking algorithm based on the spherical polar coordinate in [21]. It can only locate the attacked plant components rather than the exact attacked joint ends in some cases, though the proposed scheme has a strong ability to detect malicious attacks.

The proposed scheme in this paper is an improved algorithm compared with the previous works[22, 21]. As described in Section 4.4, it yields a strong ability to detect and locate the attacked plant components and joint ends accurately. Furthermore, it needs no additional information to be kept for watermarked process plant models. Therefore, it is more useful in the practical application.

6 Conclusion and future work

In this paper, we investigate the problem of topology authentication for process plant models. These models, compared with traditional mechanical CAD drawings, feature their intrinsical complex topological relation rather than geometrical shape. We proposed a semi-fragile watermarking scheme to cope with the topology authentication problem. The topological relation among joint plant components is employed to generate the content-based watermark bits. These topology sensitive watermark bits are then embedded into the similarity transformation invariant of each mark connection point. Both theoretical analysis and experimental results have demonstrated that our scheme has a strong ability in detecting and locating various topology attacks. Meanwhile, our scheme is robust against various non-malicious attacks.

There are also some limitations that will motivate our future research. Currently, our scheme can only authenticate the integrity of topological relation of process plant models. However, geometrical parameters of plant components are also crucial for the automatic generation of construction documents, such as isometrics, orthographics, etc. Hence, in our future work, we hope to take both of the geometrical and topological information into consideration for integrity authentication and verification.

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