Complements and Enhancements of Position Tolerance for Axis and Derived Line Imposed by ISO Standards

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***Abstract*—According to the ISO Geometrical Product Specification (GPS), position tolerance can be used to specify the axis and derived line in 2D technical drawings using a diameter symbol within a perpendicular datum system. For an inclined axis, the inset of a component surface without a diameter symbol in a nonperpendicular datum system in 3D tolerancing is not explicitly explicated, with a lack of examples in ISO GPS standards. Moreover, there exists a contraction using position tolerance for the derived line inside ISO standards. This causes incomprehension, ambiguous interpretations, and definition gaps using the position tolerance in practice. This paper suggests a new approach for establishing a holistic systematology with explicitly defined definitions and examples of position tolerance to complete and enhance the ISO standards. This research is based on the analysis of function-oriented physical behaviors of the axis and derived line of a component on a theoretical level. An improved systematology for a functional explicit definition of position tolerance is formulated, which eliminates the deficits of ISO GPS.**

***Index Terms*—Position tolerance, geometrical product specification, tolerancing and dimensioning, ISO standards, 3D tolerancing.**

I. Introduction

ISO 1101:2017 [1] is the international Geometrical Product Specification (GPS) [2]-[8] standard for tolerancing, dimensioning, and specifications for geometrical components in design and manufacturing. The basic rules, definitions, and corresponding examples of all the 14 tolerance symbols including the position tolerance are defined in the ISO 1101:2017. Another international GPS standard, ISO 1660:2017 profile tolerancing [9], describes the replacement of position tolerance of line profile tolerance by a derived line specification. However, the ISO 1101 defines only regular cases in 2D technical drawings with an axis as a tolerance feature using position tolerance with a diameter symbol, which is vertically inset into a component surface and has a perpendicularly datum system. For other nonregular cases in which the axis is not vertically inset into the component surface and without any specification of the diameter symbol in a nonperpendicular datum system in the 3D CAD program, there are no explicit definitions in the ISO 1101. Moreover, there exists a definition contraction by replacing the line profile tolerance of position tolerance between the ISO 1660 and ISO 1101. This paper is focused on the development of a new holistic systematology of position tolerance for the axis and derived line, in which their definitions are completed and enhanced according to the ISO 1101 and ISO 1660. This new approach eliminates the deficits of the ISO and offers practice-oriented examples in this paper. Previous works [10-16] concentrated more on the mathematical errors' evaluation and measurement technologies of position tolerance and code programming in the CAD system, rather than the development of function-oriented definitions and full systematologies with practical examples to complement and enhance the ISO GPS standards.

This paper is constructed as follows. Section II describes the basic important terminologies of position tolerance and datum systems from the current ISO standards. The examples from the ISO, with its corresponding deficits, are given and analyzed in this section as well. A new holistic hierarchical tree structure systematology with the corresponding examples is given in Section III. Conclusions are drawn in the last section (Section IV).

II. State Of the Art and Deficits

A. Terminology

In order to understand the research and purpose of this paper, the following important terminologies are explained with the definitions and illustrations according to the ISO standards:

- Datum feature: a real integral feature used for establishing a datum [17].
- Datum feature indicator: single features to be used for establishing datum features shall be indicated. The symbol is shown in Fig. 1 [17].

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Figure 1. Datum feature indicator. A box linked to (a) a filled or (b) an open datum triangle by a leader line. It has the same meaning as in [17].

- Datum: this is a theoretically exact reference; it is defined by a plane, a straight line, or a point, or a combination thereof [17].
- Datum system: this is a set of two or more datums established in a specific order [17]. It is not explicitly defined whether the primary, secondary, and tertiary datums shall be 90 °from each other or not [18, 19].
- Theoretically exact dimension (TED): this is a dimension indicated on technical product documentation, which is not affected by individual or general tolerance. It is indicated by a value in a rectangular frame [17]. In 3D data, the TED is omitted because all the dimensions in CAD are theoretically exact. In this paper, the TED is omitted in order to get a clear overview of technical drawings.
- Derived feature: this is a center point, median line, or median surface from one or more integral features [20]. For example, the derived feature of a pipe is the derived median line.
- Position tolerance: it can be used to specify a derived point, a straight derived line (axis), or a flat surface [1, 21, 22]. The symbol is shown in Fig. 2.

Figure 2. Position tolerance [1].

- Orientation plane indicator: this shall be indicated when the toleranced feature is a derived median line, and the width of the tolerance zone is limited by two parallel planes [1]. The indicator is shown in Fig. 3.

Figure 3**.** Orientation plane indicator [1].

- Line profile tolerance: this can be used to specify a section line or a nonstraight derived line [1, 9]. The symbol is shown in Fig. 4.

Figure 4. Line profile tolerance [1, 9].

B. *Examples from the ISO and the Corresponding Deficits*

This section illustrates the examples of the specification of a hole axis and derived line of a pipe using the position tolerance from the ISO 1101 and ISO 1660. The two corresponding concrete deficits of ISO standards will be analyzed in this section as well.

ISO Example I: Position Specification of Hole Axis and Its Deficits. Figure 5 shows the same component with two different position specifications from the ISO 1101. This component has a primary datum plane C on the bottom, a secondary datum plane A on the front, and a tertiary datum plane B on the side. These datum planes are mutually perpendicular. The datum system is established by C, A, and B. The location and orientation of the tolerance zone are with respect to the datum system [1]. In Fig. 5(a), the orientation plane indicators are applied next to the tolerance indicator. The orientation plane indicator B indicates the two parallel planes, which are parallel to the datum plane B, and the width of the tolerance zone for the holes is 0.05 mm [see Fig. 5(b)]. In analogy to the orientation plane indicator B, the orientation plane indicator A limits the width to 0.2 mm of the tolerance zone for the holes also with two parallel planes, which are parallel to the datum plane A. The notation of the second tolerance indicator, which contains the primary and secondary datum planes C and A in Fig. 5(a), is not fully described, because the tertiary datum plane B is lacking. Figure 5(b) illustrates the tolerance zone of the hole axis, which is a cuboid with different widths (0.05 mm and 0.2 mm) and it is perpendicular to the datum plane C and parallel to the datum planes A and B. In Fig. 5(c), the hole axis is specified with position tolerance using the notation of diameter symbol in front of the tolerance value 0.1 mm. The diameter symbol changes the tolerance zone from a cuboid with different widths to a cylinder with a diameter of 0.1 mm [see Fig. 5(d)]. The axis is perpendicular to the component surface or datum plane C and parallel to datum planes A and B.

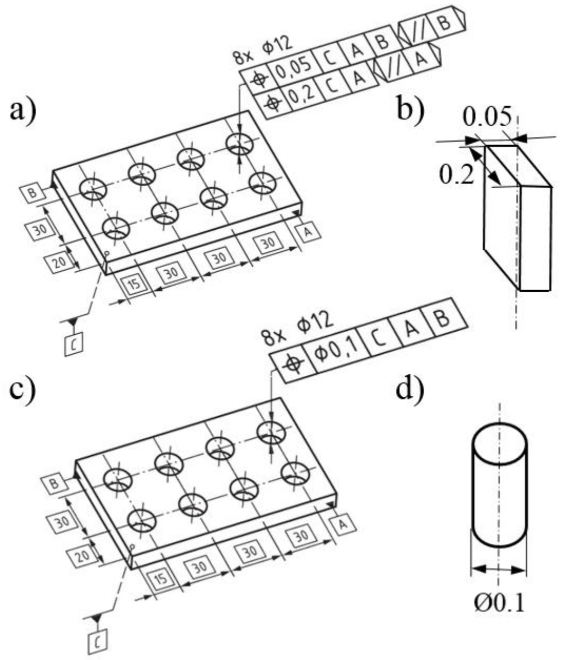

Figure 5. ISO examples for hole axis specification with position tolerance: (a) application of orientation plane indicators; (b) the corresponding tolerance zone is a cuboid with different widths; (c) application of a diameter symbol; (d) the corresponding tolerance zone is a cylinder [1].

There are no definitions in the ISO when the diameter symbol Ø is not applied in the tolerance indicator in Fig. 5(c), where the tolerance zone will be defined. Based on the ISO, the location and orientation of the tolerance zone are respected by the datum system. There are no explicit definitions or examples using position tolerance for an axis in the non–mutually perpendicular datums inside a datum system. Moreover, for a hole axis that is not a perpendicular inset of a component surface, but with an angle, the definitions of the ISO are not explicit and the corresponding examples are missing. Last but not least, the ISO defines the notation of position tolerance only in 2D technical drawings; the 3D drawing for the ISO is only a 3D perspective view of a component. It cannot indicate the function-oriented notation of position tolerance in the 3D CAD program.

Deficit 1. the following definitions and corresponding examples of position tolerance for the hole axis are either missing or not explicitly defined in ISO GPS standards:

- Tolerance zone without application of the diameter symbol.
- Non–mutually perpendicular datums inside a datum system.
- Axis not being a perpendicular inset of a component surface.
- Function-oriented notation in 3D CAD program.

ISO Example II: Position Specification of Derived Line and Its Deficit. Figure 6 is an example from the ISO 1660. The line profile tolerance [see Fig. 6(a)] defines the specification of the derived line from P to H as a united feature (UF) of the pipe with a diameter symbol in front of the tolerance value of 0.5 mm. The tolerance zone is limited by a tube enveloping sphere with a diameter equal to the tolerance value. The specification does not refer to the datum system, and the location and orientation of the tolerance zone are not constrained [9].

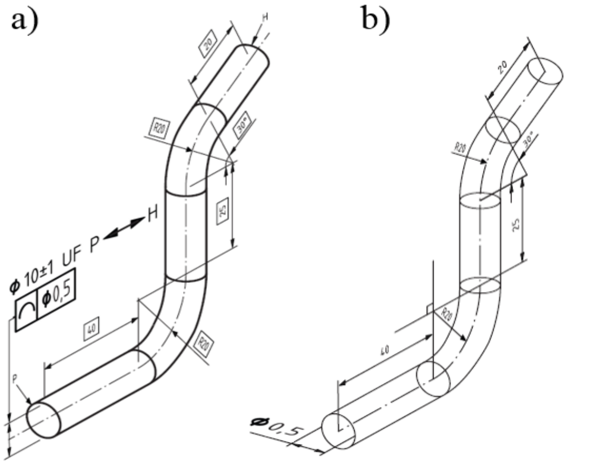

Figure 6. ISO example for derived line specification with line profile tolerance: (a) toleranced component pipe, (b) corresponding tolerance zone [9].

According to the valid ISO 1660:2017, the tolerancing specification meaning would have been the same if the position characteristic symbol had been used instead of the line profile characteristic symbol [9]. However, according to the current ISO 1101:2017, the position characteristic symbol shall not be used for nonstraight derived line [1]. This is a contradiction between the ISO 1660 and ISO 1101.

Deficit 2. A contradiction exists between the ISO 1660 and ISO 110 using the line profile characteristic symbol and position characteristic symbol by the derived line specification. ISO 1660 allows their replacement; however, the definition of ISO 1101 does not allow this replacement.

III. New Systematology of Position Tolerance

In order to eliminate the deficits of the ISO, a new systematology in Fig. 7 is developed to complement and enhance the definitions and to give corresponding examples of position tolerance of the axis and derived line based on ISO standards. In Fig. 7, the tolerance feature of position tolerance is divided into a hole axis and a derived line. The hole axis can be subdivided into a regular case (in which the component has a perpendicular datum system and the axis is vertical to the component surface) and a derivate case (in which the component has a perpendicular datum system, and the axis can be angular to the component surface). In the regular case, it can be classified into a tolerance value with or without a diameter symbol in 2D drawings and the notation of position tolerance in 3D CAD data (see Fig. 8). In analogy to the regular case, by the derivate case, the tolerance indicator with position tolerance can be classified into these three cases as well. However, under each case, it can be further subclassified into an axis that is vertical to the component surface by a perpendicular and nonperpendicular datum system and an axis that is angular to the component surface by a perpendicular and nonperpendicular datum system (see Fig. 9). The same thought model can be applied to the position tolerance without a diameter symbol; the corresponding examples and explanations are illustrated in Fig. 10. The whole application of function-oriented notation of position tolerance in 3D CAD data can be analogous to Fig. 8(c). For the derived line, it can also be divided into the position tolerance with and without a diameter symbol and notation in 3D CAD data. The corresponding examples and explanations are shown in Fig. 11. As illustrated in Fig. 7, there are only two definitions and examples which the ISO standards explicitly define using the position tolerance. The other cases which the ISO does not explicitly define will be explicated in the following figures (Figs. 8–11).

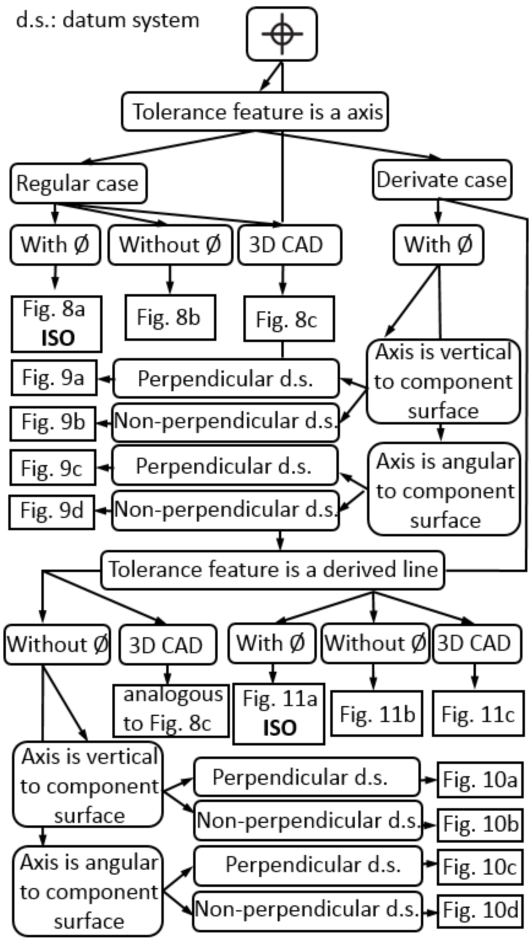

Figure 7. New systematology of position tolerance to the hole axis and derived line.

Figure 8 shows examples in the regular case from the new systematology. Figure 8(a) is a component from the ISO, which has a perpendicular datum system C, A, and B. The tolerance feature is its axis, which is specified with position tolerance of 0.08 mm with a diameter symbol. Its corresponding tolerance zone is a cylinder with a diameter of 0.08 mm, which is the tolerance value. The axis is perpendicular to the primary datum plane C and parallel to the datum planes A and B. The location and orientation of the tolerance zone with respect to the datum system C, A, and B. Figure 8(b) is the same as Fig. 8(a), but without the diameter symbol Ø in front of the tolerance value in the tolerance indicator. The definition of its tolerance zone is missing in the ISO. The new approach for this definition gap is as follows: when the tolerance value is without Ø, the tolerance zone is defined by a cuboid with the same widths, but not using the orientation plane indicator, because the widths of the tolerance zone are identical. This simplifies the technical drawing and the definition becomes clear. When position tolerance is applied on 3D CAD data, the lead line of its tolerance indicator is directly affected with the coordinate system of the axis [Fig. 8(c)], which is currently not allowed by the ISO standards. The axis is a derived feature, not a real feature, so based on the rules of the ISO, the axis must be notated with the help of dimension lines. However, the notation way in 3D CAD data, which is directly connected to the axis, shows significant benefits for the system update stabilities in the 3D CAD program. For example, when the diameter or the position of this hole changes, the position tolerance indicator will follow the axis automaticity. This is because its lead line is affected by the axis coordinate system. When the ISO notation method in 2D drawings is applied on the 3D CAD data, the position tolerance indicator will not be automatically changed when the position of the hole changes. So, in this paper, we suggest a new notation method inserted into 3D CAD data. The axis will be highlighted in the CAD by mouse clicking of the tolerance indicator. This is a pure notation of the position tolerance indicator, which does not change the definitions of position tolerance.

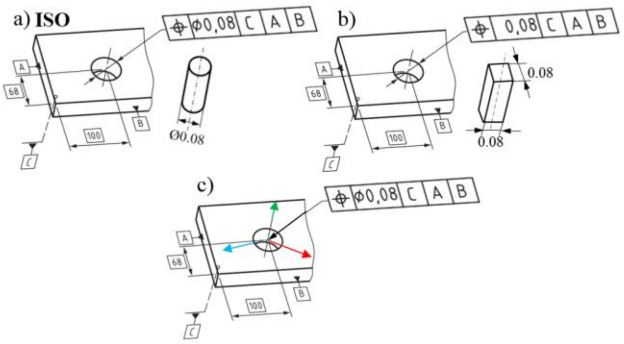

Figure 8. Regular case using position tolerance: ISO definition (a) with a diameter symbol (the tolerance zone is cylindrical [1]) and (b) without a diameter symbol (the tolerance zone is a cuboid with the same widths). (c) A function-oriented notation of the tolerance indicator by position specification in 3D CAD data.

Figure 9 illustrates the derivate cases that contain the diameter symbol in the position tolerance indicator. The definitions of tolerance zones by position tolerance in derivate cases are not explicitly defined in the current ISO. Figure 9(a) shows a component with a perpendicular datum system. The axis is perpendicular on the inclined surface of this component. According to the ISO, the tolerance zone is a cylinder, and its location and orientation shall be with respect to the datum system. In the ISO, there are only examples with a tolerance feature perpendicular or parallel to datums and a datum system; so, for the derivate case whose axis is neither perpendicular nor parallel to datums and the datum system, the explicit definitions are missing. Due to the function of this hole, its axis can be only moved inside the inclined surface, and therefore the orientation and location of its tolerance zone form a cylinder, which is symmetric around the theoretical exact axis on the drawing. The cylindrical tolerance zone is drawn in Fig. 9(a) next to the component in order to give a clear presentation. For a component with a nonperpendicular datum system, shown in Fig. 9(b), its tolerance zone is still cylindrical because of the diameter symbol, and the location and orientation of the tolerance zone are still around the theoretical exact axis. Due to the fact that this tolerance zone around the axis can indicate the function of the hole, it can only be moved along the surface. When an axis is not perpendicularly inserted into a surface [see Figs. 9(c) and 9(d)], its tolerance zone will always be cylindrical because of the diameter symbol and because the location and orientation of the tolerance zone are always around the theoretical exact axis. No matter whether the axis is perpendicular or angular on the surface, it does not change the function of the hole axis. No explicit explanations on the location and orientation of the tolerance zone with respect to a perpendicular or a nonperpendicular datum system are defined in the current ISO standards, and the corresponding examples are missing. This section presents the definition and offers the corresponding examples.

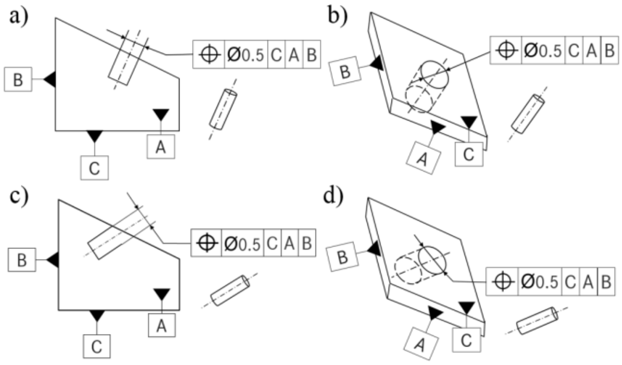

Figure 9. Derivate case with a diameter symbol: (a) the axis is vertical on a component surface with a perpendicular datum system; (b) the axis is vertical on a component surface with a nonperpendicular datum system; (c) the axis is angular on a component surface with a perpendicular datum system; (b) the axis is angular on a component surface with a nonperpendicular datum system.

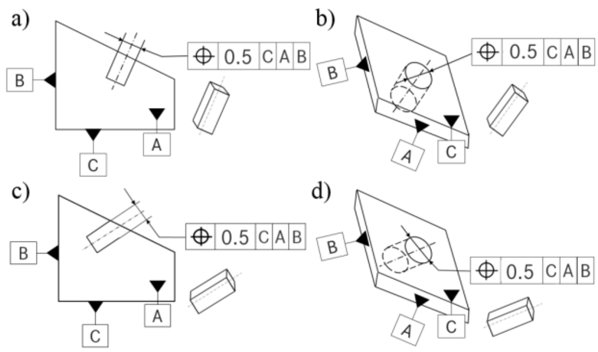

Figure 10. Derivate case without a diameter symbol: (a) the axis is vertical on a component surface with a perpendicular datum system; (b) the axis is vertical on a component surface with a nonperpendicular datum system; (c) the axis is angular on a component surface with a perpendicular datum system; (b) the axis is angular on a component surface with a nonperpendicular datum system.

Figure 10 illustrates derivate cases without a diameter symbol in front of the tolerance value in the position tolerance indicator, whose definition of the tolerance zone is not defined in the current ISO standards. Analogous to Fig. 9, the location and orientation of the tolerance zone are around the theoretical exact axis, which is drawn with TEDs in the technical drawing. The function of the axis stays the same, which is movable inside the surface. This is why the location and the orientation of the tolerance zone are the same as in Fig. 9. The only difference is the form of the tolerance zone by not inserting the diameter symbol that its form from cylindrical to cuboid with the same widths. The explicit definitions, explanations, and corresponding examples from Figs. 8–10 eliminate the first deficits that were described in the previous section.

Figure 11 illustrates the specification of a derived line using the position characteristic symbol, which replaces the line profile characteristic symbol based on ISO 1660 [9]. Due to the fact that the specification does not reference datums and the datum system, the location and orientation of the tolerance zone are not constrained. Figure 11(a) shows the example from the ISO with a diameter symbol in front of the tolerance value of 0.5 mm in the tolerance indicator. In the ISO, its tolerance zone is explicitly defined by tube enveloping spheres with a diameter equal to the tolerance value. However, for the specification of this derived line without applying a diameter symbol in the tolerance indicator [see Fig. 11(b)], the form of the tolerance zone is not defined in the ISO. Figure 11(b) shows the analyzed form of the tolerance zone, which fits the function of the derived line and the logic of the notation system. Every intersection of the tolerance zone is a square that has the same width of 0.5 mm. Therefore, an explicit definition of the form of the tolerance zone without using a diameter symbol is presented. However, the location and orientation of the tolerance zone cannot be defined because the datum system is missing. So, the tolerance zone can be rotated around the derived line, which is illustrated in Fig. 5(b) in the circle with square intersections. Figure 11(c) shows the new notation method of the position tolerance indicator of this component in a 3D CAD program, where the lead line is directly connected to the coordinate system in the derived line. When the tolerance indicator is clicked on by a mouse, the tolerance feature-derived line will be highlighted. Therefore, the annotation Ø 10 ± 1 UF from P to H can be omitted. This is because the range of the tolerance feature will be automatically highlighted. This notation method has an update stability in the 3D CAD program during the geometry variation of the component.

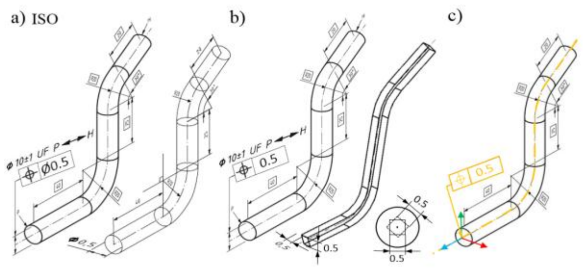

Figure 11. The toleranced feature is a derived line using position tolerance: (a) an ISO example with a diameter symbol and its cylindrical tolerance zone; (b) the same component without using a diameter symbol and its tolerance zone; (c) a new notation method of the position tolerance indicator in 3D CAD data.

When trying to eliminate the second deficit that was described in the previous section, a contradiction was found to exist between ISO 1660 and ISO 1101 using the position characteristic symbol instead of the line profile characteristic symbol. This paper suggests that the International Technical Committee ISO/TC 213 [23] should amend either the definition of ISO 1101 or the definition of ISO 1660 for position tolerance. The easiest way is to delete the following sense in ISO 1660: "*The meaning would have been the same if the position characteristic symbol had been used instead of the line profile characteristic symbol*."

IV. Conclusion

In this paper, we presented a novel approach for complementing and enhancing the definitions of position tolerance for the axis and derived line imposed by ISO standards. A new function-oriented systematology with explicit definitions and corresponding practice-oriented examples of position tolerance for the axis and derived line was developed. The deficits, contradictions, and definition gaps of the ISO were analyzed and eliminated by the new systematology with a hierarchic tree structure. Moreover, some constructive suggestions were offered to the International Technical Committee for ISO geometric product specification standards. Future work should involve applying the approaches to other complex geometries with other complex tolerance features.

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