Introduction

The closed loop programming model makes a machine more accurate by allowing it to iteratively correct a machining program until the part being machined is within tolerance. The model is an extension of the STEP-NC model defined by ISO 14649 and implemented by ISO 10303-238.

The closed loop programming model assumes errors in the machining are detected using a measuring device. It expects surfaces on a workpiece to be measured by the device and delivered to the programming model as a STEP file. The new constructs in the closed loop programming model then evaluate the returned surfaces to see if there are errors that can be corrected. If so a compensation_workingstep is activated to correct the machining using a three or five axis transformation. The correction can be applied to machining setup data, machining toolpath data, or machining operation parameter data. The process of making the correction can be divided into stages to allow the actual improvement in quality for an early stage to determine the safe compensation for the remaining stages.

Industrial automation systems and integration
Physical device control
Data model for computerized numerical controllers
Part 18: Closed Loop Programming Model

1 Scope
This part of ISO 14649 specifies the process data which is needed to enable closed loop machining. These data elements describe the interface between a measurement device and a computerised numerical control programme. The measurement device measures surfaces and delivers them to the computerized numerical control programme as a STEP product model. The closed loop machining program processes these surfaces and builds a representation that is used to adjust the machining programme to make it more accurate.

2 Normative references

3 Terms and definitions
For the purposes of this part of ISO 14649 the following terms definitions and abbreviations are used:

4 Closed Loop Machining data

4.1 Header and references

The following listing gives the header and the list of entities which are referenced within this schema.

```
SCHEMA closed_loop_machining_schema;
REFERENCE FROM measure_schema (* ISO 10303-41 *) (
      length_measure,
      ratio_measure
);
REFERENCE FROM support_resource_schema (* ISO 10303-41 *) (
      identifier,
      text
);
REFERENCE FROM geometry_schema (* ISO 10303-42 *) (
      axis2_placement_3d,
      cartesian_point,
      cartesian_transformation_operator_3d,
      direction,
      elementary_surface
      geometric_representation_item,
      planar_surface
);
REFERENCE FROM machining_schema (* ISO 14649-10 *) (
      setup,
      trajectory,
      two5d_manufacturing_feature,
      workingstep,
      workpiece,
      workpiece_probing
);
REFERENCE FROM tolerance_schema (* ISO 10303-10?? *) (
      geometric_tolerance,
      geometric_dimension
);
```

4.2 Compensation Workingstep

A closed loop program contains one or more compensation workingsteps. Each compensation workingstep uses a measurement _evaluation process to compute a correction for the compensation definition. The lower error determines if a correction is necessary. The upper error determines a limit to the size of the compensation before a warning is issued to the operator and processing stops. The compensation_stage determines how much of the error is to be fixed in this workingstep.

```
ENTITY compensation_workingstep SUBTYPE OF (workingstep);
      its_measurements        : measurement_evaluation;
      its_corrections         : compensation_definition;
      its_lower_error         : OPTIONAL length_measure;
      its_upper_error         : OPTIONAL length_measure;
      its_pass                : compensation_stage;
END_ENTITY;
```

its_measurements	The surfaces that are to be measured using an algorithm selected by the types in the data.
its_corrections	The items in the programming model that are to be modified using the correction determined by the measurement.

its_lower_error	If the error determined by the measurement evaluation is below this value then no correction is necessary.
its_upper_error	If the error determined by the measurement evaluation is above this value then the error is too large to be corrected and the machining stops.
its_pass	If the error is being corrected in multiple passes then this attribute defines how much material is to be removed in this pass for example 20%.

4.3 How to measure

4.3.1 Measurement Evaluation

A measurement evaluation determines the error that must be compensated.

```
ENTITY measurement_evaluation ABSTRACT SUPERTYPE;
      its_id                  : identifier;
      its_measurement_piece   : workpiece;
      reference_frame         : OPTIONAL axis2_placement_3d_measurement;
      its_error               : OPTIONAL length_measure;
      its_correction          : OPTIONAL
                                     cartesian_transformation_operator_3d;
END_ENTITY;
```

its_id	Each measurement evaluation has a unique identifier.
Its_workpiece	A product model containing the surfaces computed by the measurement system.
reference_frame	The coordinate system for the geometry measured in this evaluation. If the measurement device is mounted on the machine tool then its coordinate system can change each time it is mounted. The reference frame determines the location of a defined point on the machine tool in the coordinate system used for this round of measurements.
its_error	The error computed by the measurement evaluation. This error will be compared with the lower and upper bound errors of the compensation workingstep. If there is no error value present then the measure has not yet been evaluated.
its_correction	A transformation operator that corrects the measured error by mapping an entity computed by the measurement evaluation onto a reference entity. If there is no value present but an error has been computed then no correction was made by the compensation workingstep.

4.3.1.1 Axis2_placement_3d_measurement

This type of measurement evaluation computes an axis2_placement_3d entity. The error computed by the measurement evaluation is the distance between the origin of the computed axis2_placement_3d entity and the origin of the reference definition axis2_placement_3d entity. The compensation computed by the measurement evaluation is the transformation that moves the computed axis2_placement_3d entity onto the reference axis2_placement_3d entity.

```
ENTITY axis2_placement_3d_measurement ABSTRACT
      SUBTYPE OF (measurement_evaluation);
      reference_definition    : axis2_placement_3d;
      computed_definition     : OPTIONAL axis2_placement_3d;
END_ENTITY;
```

reference_definition	An axis2_placement_3d entity in the machining program that will be compared with the measured axis2_placement_3d entity computed by the subtypes to determine an error and a compensation.
computed_definition	The axis2_placement_3d computed computed by the measurement. If no value is present then the measure has not yet been evaluated.

4.3.1.1.1 Three_face_corner_measurement

This type of measurement evaluation computes an axis2_placement_3d entity by measuring three planar surfaces on a corner. The normal of the first face is the z axis. The intersection point of the three faces determines the origin of the axis. The normal of the last face is the reference direction.

```
ENTITY three_face_corner_measurement
      SUBTYPE OF (axis2_placement_3d_measurement);
      first_face        : planar_surface_measurement_result;
      second_face       : planar_surface_measurement_result;
      third_face        : planar_surface_measurement_result;
(*
Informal proposition:
No two of the three faces shall be coplanar.
*)
END_ENTITY;
```

first_face	The normal of the first measured face is the Z axis of the result.
second_face	The intersection of the three faces is the origin.
third_face	The normal of the third face is the reference direction of the result.

```
Note: if a face does not need to be measured because it is known to be
correct then a value can be set in the measurement_result entity to show that
it is correct and if so the axis2_placement_3d will be computed using the
value of the as_designed face instead.
```

4.3.1.1.1.1 Six_point_corner_measurement

This type of three face corner evaluation uses an on machine probe to evaluate the three faces of the corner. Three points are necessary to define the first face but only two points are necessary for the second face and one point for the third because the three faces must define a rectilinear corner.

```
ENTITY six_point_corner_measurement
      SUBTYPE OF (three_face_corner_measurement);
      its_first_face_probes   : OPTIONAL SET[1:3] OF workpiece_probing;
      its_second_face_probes  : OPTIONAL SET[1:2] OF workpiece_probing;
      its_third_face_probe    : OPTIONAL workpiece_probing;
(*
Informal proposition:
If no value is set for the probes of a face then the measurement relationship
of that face must be set to nominal_is_correct.
*)
END_ENTITY;
```

its_first_face_probes	Three points on the first face.
its_second_face_probes	Two points on the second face.
its_third_face_probes	One point on the third face.

```
Note: The workpiece_probing entity measures a point on a surface and is
defined in ISO 14649-10.
```

4.4 What to measure

4.4.1 Measurement Result

A measurement result describes the as-measured geometry of a geometric representation item.

```
ENTITY measurement_result;
      its_nominal_geometry    : geometric_representation_item;
      its_evaluated_geometry  : OPTIONAL geometric_representation_item;
      assume_nominal_correct  : BOOLEAN;
      its_tolerances          : SET [0:?] OF geometric_tolerance
      its_dimensions          : SET [0:?] OF geometric_dimension
END_ENTITY;
```

its_nominal_geometry	A geometric item in the model that is to be measured.
its_evaluated_geometry	The geometric item computed by the measurement system. If no item is found during a measurement evaluation and the nominal cannot be assumed to be correct then there is an error in the program and the machining must be stopped.
assume_nominal_correct	The item does not need to be measured because the nominal can be assumed to be correct. For example, because the face has been machined and it being placed on a flat clean surface of the machine tool
its_geometric_tolerances	The subset of the geometric tolerances defined for the nominal geometry item that are applicable to this measurement relationship.
its_geometric_dimensions	The subset of the geometric dimensions defined for the nominal geometry item that are applicable to this measurement relationship.

Note: What to do if a geometric tolerance or geometric dimension is exceeded before or after a compensation is corrected is not (yet?) defined. However a software system might choose to display the surfaces as red, green or yellow depending on if they it is in or out of tolerance before or after the compensation.

4.4.1.1 Elementary Surface Measurement Result

An elementary surface measurement result describes the as-measured geometry of an elementary surface.

```
ENTITY elementary_surface_measurement_result SUBTYPE OF
            (measurement_result);
      SELF\measurement_result.its_nominal_geometry
                              : elementary_surface;
      SELF\measurement_result.its_evaluated_geometry
                              : OPTIONAL elementary_surface;
END_ENTITY;
```

its_nominal_geometry	An elementary surface that is to be measured.
its_evaluated_geometry	The elementary surface computed by the measurement system.

4.4.1.1.1 Planar Surface Measurement Result

A planar surface measurement result describes the as-measured geometry of a planar surface.

```
ENTITY planar_surface_measurement_result SUBTYPE OF
            (elementary_surface_measurement_result);
      SELF\measurement_result.its_nominal_geometry
                              : plane;
```

```
      SELF\measurement_result.its_evaluated_geometry
                              : OPTIONAL plane;
END_ENTITY;
```

its_nominal_geometry	A plane that is to be measured.
its_evaluated_geometry	The plane computed by the measurement system.

4.5 What to correct

4.5.1 Compensation_definition

A compensation definition defines one or more items in the machining program that are to be corrected by a compensation workingstep.

```
ENTITY compensation_definition ABSTRACT SUPERTYPE OF
      (setup_compensation, toolpath_compensation, feature_axis_compensation)
      its_id            : identifier;
      description       : OPTIONAL text;
END_ENTITY;
```

its_id	Each compensation has a unique identifier.
description	Optional description of the purpose of the compensation

```
Note: The different types of compensation items can be combined using AND/OR
inheritance.
```

4.5.1 Setup_compensation

The item to be corrected is a workplan setup. The correction is made by applying cartesian_transformation_operator_3d computed by the measurement evaluation to the axis2_placement_3d defined by the its_origin attribute of the setup.

```
ENTITY setup_compensation SUBTYPE OF compensation_definition;
      setup_for_correction   : setup;
END_ENTITY;
```

setup_for_correction	A workplan setup that is to be corrected by the compensation workingstep.

4.5.1 Toolpath_compensation

The items to be corrected are toolpath trajectories. The correction is made by applying cartesian_transformation_operator_3d computed by the measurement evaluation to each point in the trajectory. If the toolpath is five axis then the operator is also applied to each axis direction.

```
ENTITY toolpath_compensation SUBTYPE OF compensation_definition;
      paths_for_correction    : SET [1:?] of Trajectory;
      correction_points       : OPTIONAL SET of cartesian_point;
END_ENTITY
```

paths_for_correction	These toolpaths shall be corrected.
correction_points	If defined then only these points in the toolpaths shall have their locations and axes corrected. For example, the points on the toolpath that machine the surface that has been evaluated.

```
Note: The correction of toolpaths containing arcs is not yet undefined. After
the toolpath points have been moved the arcs can be corrected by changing
their radii or centers or both.
```

4.5.2 Feature_placement_compensation

The items to be corrected are toolpath trajectories. The correction is made by applying the cartesian_transformation_operator_3d computed by the measurement evaluation to the axis2_placement_3d defined by the feature placements of the listed manufacturing features.

```
ENTITY feature_placement_compensation SUBTYPE OF compensation_definition;
      features_for_correction : SET[1:?] of two5d_manufacturing_feature;
END_ENTITY
```

features_for_correction These features shall have their feature placements corrected.

4.6 How to control the correction

4.6.1 Compensation_stage

Compensations are necessary because the original program did not operate correctly. However, in theory the program was correct and the same factors that affected the original program, material hardness, tool bending, machine tool accuracy will also affect the compensated program. The compensation_stage entity allows the effect of a correction to be evaluated scientifically with test cuts being made to see how much material is being removed and the results of those test cuts being used to control subsequent cuts.

```
ENTITY compensation_stage ABSTRACT SUPERTYPE OF (ONEOF (single_pass,
            sequence_pass));
      subtract          : OPTIONAL boolean;
END_ENTITY
```

subtract — Normally the correction is added to the compensation definition. If this attribute set then the correction shall be subtracted.

4.6.1.1 Single_pass

A single pass compensation removes material to correct a fixed ratio of the error computed by the measurement evaluation.

```
ENTITY single_pass SUBTYPE OF compensation_stage
      correction_ratio  : ratio_measure;
END_ENTITY
```

correction_ratio — How much of the error is to be corrected. For a setup correction this might be 100%. For the first cut for a tool path correction it might be 10%.

4.6.1.2 Sequence_pass

A sequence pass correction uses a test cut to adjust how much material should be removed in this pass..

```
ENTITY sequence_pass SUBTYPE OF compensation_stage;
      its_error               : measurement_evaluation;
      correction_ratio        : ratio_measure;
      its_lower_correction    : ratio_measure;
      its_upper_correction    : ratio_measure;
      its_test_cut            : OPTIONAL test_cut;
END_ENTITY
```

its_error — The error being corrected by this sequence of passes.
correction_ratio — How much of the error defined by the measurement evaluation is to be corrected in this pass.

its_lower_correction	Stop and warn the operator if the result of the test cut reduces the error correction below this ratio.
its_upper_correction	Stop and warn the operator if the result of the test cut increases the error correction above this ratio.
test_cut	Use the effectiveness of the following test cut to adjust the correction ratio. For example if the test cut had a targeted error reduction of 10% but an effective error reduction of 8% then the correction values (position and axis) computed in this pass will be increased by 25%.

4.6.1.3 Test_cut

A test cut measures the effectiveness of a compensation by taking measurements before and after a test cut. The difference in the error computed by the two measurement evaluations is compared to the target_percentage and if it is less than the target percentage then the correction of the compensation using the test cut is increased and if it less then it is decreased. For example, if the target percentage is 20% but the error of the first cut was reduced by only 10% in the second cut then the correction in the compensation will be increased by 50%.

```
ENTITY test_cut;
      its_target_percentage   : ratio_measure;
      its_first_cut           : measurement_evaluation;
      its_second_cut          : measurement_evaluation;
END_ENTITY;
```

its_target_percentage	The targeted reduction in the measurement error between the first and second cuts.
its_first_cut	The measurement error before the test cut.
Its_second_cut	The measurement error after the test cut.