A Computational Construction Grammar Framework for Modelling Signed Languages

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Abstract

Constructional approaches to signed languages are becoming increasingly popular within sign language linguistics. Current approaches, however, focus primarily on theoretical description, while formalization and computational implementation remain largely unexplored. This paper provides an initial step towards addressing this gap by studying and operationalizing the core mechanisms required for representing and processing manual signed forms using computational construction grammar. These include a phonetic representation of individual manual signs and a formal representation of the complex temporal synchronization patterns between them. The implemented mechanisms are integrated into Fluid Construction Grammar and are available as a module within the Babel software library. Through an interactive web demonstration, we illustrate how this module lays the groundwork for future computational exploration of constructions that bidirectionally map between signed forms and their meanings.

1 Introduction

Constructional approaches to signed languages are becoming increasingly popular within sign language linguistics (see Wilcox and Martínez (2025) for an overview). One possible reason for this popularity is construction grammar's potential to address key challenges in the field. The view on lexicon and grammar as a continuum, for instance, can help resolve longstanding problematic distinctions between grammatical and lexical signs on the one hand (Lepic and Occhino, 2018; Lepic, 2019), and gestural and linguistic signs on the other hand (Lepic and Occhino, 2018; Occhino and Wilcox, 2017; Wilcox and Xavier, 2013).

Despite its popularity, construction grammar has primarily been used for the theoretical description of sign language constructions (e.g., Lepic and Occhino, 2018; Schembri et al., 2018; Lepic, 2019; Wilcox and Occhino, 2016; Hou, 2022a,b; Wilcox and Martínez, 2020; Martínez et al., 2019; Wilcox et al., 2022; Johnston and Ferrara, 2012) while formalization and computational implementation of these constructions remain relatively unexplored. One exception is the work by van Trijp (2015), who provides a proof-of-concept implementation of two French Sign Language (LSF) constructions. Other computational models rely on formalisms such as Head-Driven Phrase Structure Grammar (HPSG) (Elliott et al., 2008), Role and Reference Grammar (RRG) (Murtagh, 2011b) or sign language specific production rules (Filhol et al., 2017). Except for van Trijp (2015)'s bidirectional approach, most existing computational work focuses solely on sign language production through avatar systems.

This paper presents an initial step towards addressing these gaps by studying and operationalizing the core mechanisms needed for representing and processing signed languages bidirectionally using a computational construction grammar framework. The development of such a framework is beneficial as it allows linguistic hypotheses to be formalized and verified on large linguistic corpora (van Trijp et al., 2022).

The implemented mechanisms include a phonetic, language-agnostic representation of individual manual signs and a formal description of the complex temporal synchronization patterns between them. These mechanisms are integrated into Fluid Construction Grammar (FCG) (Steels, 2011; Beuls and Van Eecke, 2023; van Trijp et al., 2022), a computational construction grammar framework that operationalizes the basic tenets of construction grammar (Steels, 2011; van Trijp et al., 2022; Beuls and Van Eecke, 2023, 2025). The developed framework is available as a module within the Babel software library [1], a toolkit containing all

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[1] Download information is available at: `https://emergent-languages.org`

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necessary modules for constructional language processing using FCG (Nevens et al., 2019; Loetzsch et al., 2008). While this module is an initial step towards bidirectional processing of sign language, more work is needed to scale our approach towards different research contexts and large-scale corpora.

To demonstrate the use of the framework, we provide an interactive web demonstration alongside this paper. It illustrates how a French Belgian Sign Language (LSFB) utterance can be comprehended and produced, showcasing the potential of our framework for future computational exploration of sign language constructions.

The remainder of this paper is structured as follows. First, we review existing representation systems (Section 2) and computational models (Section 3) for signed languages. Then, we introduce the implemented mechanisms for representing and processing manual signed forms, which are available as a module within the Babel framework (Section 4). Afterward, we illustrate the use of this module through an interactive web demonstration (Section 5). Finally, we conclude the paper (Section 6).

2 Representing signed forms

Accurately representing signed forms is one of the main challenges in developing computational models of sign language. Sign language expressions include movements produced by the entire upper body, including manual (hands) and non-manual articulators (face, head, eyes, shoulders, etc.). These movements can overlap in time, resulting in simultaneous/multilinear structures which cannot easily be captured using linear representation systems (Huenerfauth, 2006; Filhol and Braffort, 2012; Filhol, 2012). In addition, signers make extensive use of the three-dimensional space in front of the upper body to introduce and manage referents (Wilcox and Martínez, 2020). As a result, representations should include a fine-grained model of this three-dimensional space. Despite the challenges involved, several types of representation exist, including video, glosses, formal notation systems and avatar-specific representations.

The most frequently used format for representing signed expressions is video. It accurately captures the simultaneous nature of signing and is relatively easy to collect. However, it generally needs to be complemented with additional information for the purpose of linguistic description/modelling (Crasborn, 2015). Glosses are lexical labels which describe the prototypical meaning of a sign using words from the ambient spoken language. They do not provide any information about the internal structure of a sign and focus primarily on manual activity. In contrast, formal notation systems such as SignWriting (Sutton, 1995) or HamNoSys [2] (Prillwitz et al., 1987; Hanke, 2004) describe the sublexical structure of signs using a set of iconic symbols. This sublexical structure is typically described using a set of manual (hand shape, orientation, location and movement), and non-manual parameters (e.g. eye-gaze, brow, shoulder or head movements, etc.). Finally, avatar-specific representations capture the sublexical structure of signs from an animation perspective rather than a linguistic one, resulting in detailed descriptions of joint positions and rotations (Naert et al., 2020).

With the exception of video-based and some avatar-specific representations, most systems focus on describing isolated signs. Although these descriptions often can be concatenated, they fail to accurately represent the multilinearity of continuous signed expressions. For instance, while HamNoSys allows concatenation of individual sign descriptions to represent utterances, it lacks the capacity to represent instances where articulators act independently from each other, each producing forms with different start and end times (Filhol, 2012; Filhol and Braffort, 2012).

In linguistic research, this issue is addressed using multilayered annotation tools such as ELAN (Crasborn and Sloetjes, 2008; Dreuw and Ney, 2008) and ILEX (Hanke and Storz, 2008). They enable multiple annotation tiers to be aligned with a single time track, often derived from a video recording. Using this methodology, one layer can be created for each articulator and aligned to the time track of the video. Temporal relationships are conveyed implicitly through the start and end times of the recorded segments.

Another approach has been explored within the field of avatar synthesis, where systems such as the partition/constitution (Huenerfauth, 2004) and AZalee model (Filhol and Braffort, 2012; Filhol, 2012) explicitly describe temporal relationships between articulators. The partition/constitution model represents the structure of signed utterances through hierarchical syntax trees, where nodes branch into child nodes using constitution or par-

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[2] Hamburg Notation System

tition (Huenerfauth, 2004). Constitution denotes traditional sequential branching, while partition accounts for simultaneous production. This hierarchical framework enables the modelling of complex synchronisation patterns across multiple articulators. However, synchronisation is constrained by the syntactic structure of the utterance. In contrast, the AZalee model supports a more flexible representation, allowing for the free arrangement of articulator movements by defining temporal relationships directly between their start and end boundaries (Filhol and Braffort, 2012; Filhol, 2012).

3 Computational Models of Sign Language

Computational models of sign language are relatively scarce, especially those that handle both language production and comprehension. While some work has focussed on producing sign language utterances using a grammatical model, little to no attention has been paid towards comprehending the semantic structure of sign language expressions. For production, several grammatical frameworks have been used to support avatar synthesis, including Head-Driven Phrase Structure Grammar (HPSG), Role and Reference Grammar (RRG) and AZee Production rules. For bidirectional processing, van Trijp (2015) explored the use of FCG.

The ViSiCAST and eSIGN projects use HPSG (Pollard and Sag, 1994) within a translation system from English to British Sign Language (BSL) (Elliott et al., 2008). The translation process involves multiple steps, including the use of BSL-specific HPSG rules that transform a semantic Discourse Representation Structure (DRS) into HamNoSys format (Elliott et al., 2008; Marshall and Sáfár, 2004, 2002; Sáfár and Glauert, 2010). The grammar includes 50 lexical and 9 grammatical rules and handles aspects like space, plurality, sentence types, and pronominal reference (Elliott et al., 2008; Marshall and Sáfár, 2004, 2002; Sáfár and Glauert, 2010). The HamNoSys output can be rendered into an XML-format which drives avatar animation (Kennaway, 2004).

Murtagh (2011b,a) first explored the use of RRG (Van Valin Jr. and Foley, 1980; Van Valin Jr., 1992) as a grammatical model to drive animation of Irish Sign Language (ISL). RRG is a functional theory which focusses primarily on the relationship between semantic, pragmatic, and syntactic structure (Van Valin Jr. and Foley, 1980; Van Valin Jr., 1992). The RRG grammar for ISL maps a semantic representation to a syntactical structure which represents manual, non-manual and temporal information (Murtagh et al., 2022). It can be transformed into a more detailed format which drives avatar animation (Murtagh et al., 2022). Amongst other aspects, the RRG approach focusses on modelling different verb types of ISL (Murtagh, 2020), including so-called directional/agreement verbs, which use the signing space to refer to arguments. While bidirectional, RRG has mainly been applied to sign language production (Murtagh et al., 2022).

AZee avoids spoken language categories such as noun, verb or adjective and describes sign language grammar using a set of production rules (Filhol et al., 2017). Each rule maps a semantic function to a score of time-aligned articulator movements. The output of one rule can serve as an argument to another, creating complex structures which drive avatar animation (Filhol et al., 2017). AZee rules have mostly been developped for French Sign Language (LSF), focussing on a wide range of linguistic phenomena, including interrogation (Martinod and Filhol, 2024), non-manual gestures (Challant and Filhol, 2024; Filhol et al., 2014), usage of space (Filhol and McDonald, 2022), and plurality (Martinod et al., 2022). The rules developped for LSF achieve 94% coverage on a moderately sized corpus (Challant and Filhol, 2022) and ongoing work seeks to expand this coverage (Challant and Filhol, 2024; Martinod et al., 2022).

Finally, van Trijp (2015) explores the use of computational construction grammar for sign language processing. He provides a proof-of-concept implementation of two LSF constructions using the FCG framework: a construction that handles the modification of sign parameters (i.e., hand shape, orientation, movement, location) to alter the meaning of a sign, and a construction which deals with the inherent multilinearity of continuous signed expressions (van Trijp, 2015). In contrast to other approaches discussed in this section, the FCG approach proposed by van Trijp (2015) is bidirectional, allowing language production and comprehension. The proof-of-concept implementations show the potential of computational construction grammar (specifically FCG) for modeling signed languages.

4 A Computational Construction Grammar Framework for Modelling Signed Languages

The main objective of the proposed framework is to support the computational exploration of sign language constructions in comprehension and production. To achieve this, we identify three core properties:

1. **Phonetic representation:** The framework should accurately represent the realisation of manual sign forms, including use of three dimensional space and the shape, orientation, location and movements of the hands.
2. **Multilinear representation:** The framework should provide explicit temporal relations between manual articulator movements, capturing the inherent multilinear nature of signed languages.
3. **Bidirectional:** The framework should allow bidirectional processing between signed forms and their meanings.

The remainder of this section describes how we integrate each of these properties into the proposed framework for sign language processing and release it as a module within the Babel framework.

4.1 HamNoSys: Phonetically Representing Signed Forms

Before 1960, there was an overall consensus that sign language forms lacked internal structure, making them unfit for linguistic study. This consensus changed after William Stokoe published his Pioneering work on American Sign Language (ASL) phonology in 1960 (Stokoe, 1960). Stokoe argued that, similar to spoken forms, signed forms have internal structure, determined by three main parameters: hand configuration (including the shape and orientation of the hand), location and movement (Stokoe, 1960). To support his claims, Stokoe identified minimal pairs in ASL, where only one of these three parameters distinguishes the two forms, illustrating their contrasting ability within the language. While Stokoe's work was phonological, his theory fuelled many phonetic theories and writing systems for signed forms. These often describe the structure of the sign using Stokoe's basic parameters (handshape, orientation, location and movement). Modern phonetic theories and writing systems also include non-manual features (facial expressions or shoulder and head movements).

HamNoSys (Hamburg Notation System) is one of the writing systems building on Stokoe's theory for sign structure. It relies on a set of iconic glyphs to represent hand shape, orientation, location, and movement, along with non-manual components. It is a phonetic alphabet that was created as a sign language counterpart to the International Phonetic Alphabet[3](IPA). Like IPA, it contains symbols that can be used to describe the phonetic realisation of signs in any sign language. HamNoSys is well integrated with modern computer software, having a Unicode font and XML-based representation known as Signing Gesture Markup Language (SiGML) (Elliott et al., 2004). Through SiGML, HamNoSys strings can be converted into avatar animations using the JASigning system[4].

The basic structure of a HamNoSys representation consists of two core components: an initial posture and a set of actions (see Figure 1). The initial posture describes the shape, orientation, and location of the hands at the onset of the sign. Actions describe movements through space that might change part of the initial structure. For two-handed signs, the initial posture is preceded by a symmetry operator. This operator specifies how the non-dominant hand copies information from the dominant hand, avoiding repetition. For a more detailed description, we refer to the HamNoSys manual (Smith, 2013). Figure 1 illustrates an example of an HamNoSys representation for the sign RIVIERE (RIVER) in French Belgian Sign Language (LSFB).

We choose HamNoSys as a phonetic representation as it is language agnostic, well-documented and -integrated into modern computer software (Hanke, 2004). It contains a fine-grained model of the signing space, which is crucial for grammatical modelling. Reading and writing HamNoSys requires some initial training, but the existance of an extensive manual (Smith, 2013), unicode font, input palettes (see Hanke, 2021), and avatar software make the system easy to learn and enjoyable to use.

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[3] For more information, see: `https://www.internationalphoneticassociation.org`

[4] more information about the JASigning system: `https://vh.cmp.uea.ac.uk/index.php/JASigning`

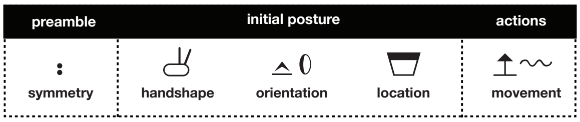


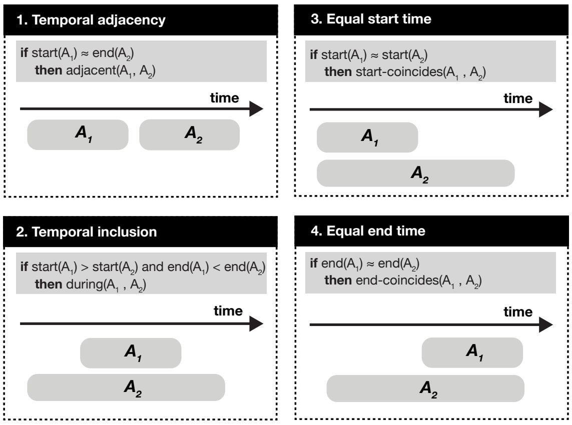
Figure 1: Example of a HamNoSys representation for the LSFB sign RIVIERE (RIVER). The sign is produced using two hands that behave symmetrically. The initial posture and actions are only described for the dominant hand, as those for the non-dominant hand can directly be inferred from them. The dominant hand's shape is a fist with the index and middle fingers extended. Fingers are oriented outwards, and the palm is directed to the left of the signer (right for the non-dominant hand). Hands move outward using a wavy motion.

4.2 Using Temporal Relationships to Convey Multilinear Structure

To describe the temporal relationships between manual signs, we first use the ELAN annotation software to align the two manual articulators to a single time-track, derived from the video-recording of the expression. Annotation files contain two layers for each of the manual articulators (four layers total). The first layer for each hand divides the time-track into individual signs, identifying each sign using its lexical ID-gloss label. The second layer provides a HamNoSys representation for each identified sign.

Afterward, the annotation file is used to extract the ID-gloss, HamNoSys representation, and temporal boundaries for each identified segment. In our multilinear representation, every articulation is modeled as a predicate that specifies its type (i.e. *two-hand-articulation*, *right-hand-articulation* or *left-hand-articulation*), and takes two arguments: a unique identifier (derived from the sign's ID-gloss) and a HamNoSys string. For every pair of articulations, we evaluate whether any of the temporal relationships illustrated in Figure 2 apply. The resulting output is a set of predicates that encode both the phonetic structure of individual manual signs and the temporal relations between them.

Figure 3 shows a multilinear representation of an LSFB question from the GeoQuery-LSFB corpus[5]. The LSFB expression is a translation of the English question *"What are the high points of states surrounding Mississippi?"*. To illustrate the use of temporal relationships, we focus on the highlighted part of the expression. The left hand produces a sign glossed as DS[BENT5]:ETAT, which depicts a state. Meanwhile, the right hand performs three sequential signs: DS:[BENT5]:ETAT+, depicting multiple states, PT:DET/LOC[1]+, a pointing sign referring to the locations of the previously introduced states, and HAUT, which refers to a high point. The multilinear representation specifies each articulation's type, unique identifier and HamNoSys representation, along with five temporal relationships: two adjacency relations between the right handed signs, an equal start relationship between DS[BENT5]:ETAT+ and DS[BENT5]:ETAT, a during relationship between PT:DET/LOC[1]+ and DS[BENT5]:ETAT, and an equal end relationship between HAUT and DS[BENT5]:ETAT.



Where ≈ denotes approximative equality (+- 100 ms)
and A_1, A_2 are unique identifiers of articulations

Figure 2: The collection of temporal relationships used within the multilinear representation of our framework. The adjacency relationship captures the sequential ordering of two articulations, while the remaining relationships describe multilinear structures involving two articulations. A single articulation can be involved in multiple relationships.

Our multilinear representation was primarily inspired by the AZalee approach, where articulators from any type can be aligned freely through their temporal boundaries and a set of temporal relationships (Filhol, 2012; Filhol and Braffort, 2012). While our representation currently only includes manual articulators, we acknowledge the importance of non-manual components for grammar modelling. Therefore, we designed the representation to be extensible, aiming to add non-manual articulation types in the future.

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[5] A resource of LSFB questions on U.S. geography, annotated with procedural semantic representations. Available at: `https://gitlab.unamur.be/beehaif/GeoQuery-LSFB`

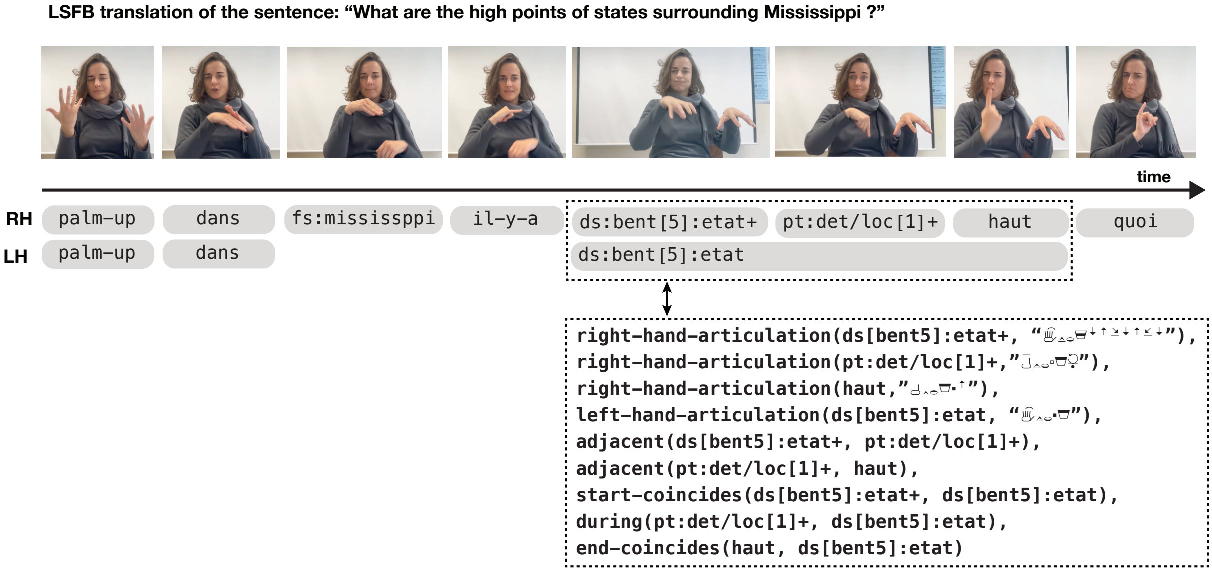

Figure 3: Example of a multilinear representation for a form in LSFB. The highlighted part of the expression contains four articulations in total, three right handed and one left handed one. Right handed articulations all occur in sequence (conveyed by two adjacency relationships), while the left handed articulation is held through time and simultaneously occurs with the sequence of right handed signs. This simultaneous occurrence is conveyed through the start-coincides, during, and end-coincides relationships in the representation.

4.3 Fluid Construction Grammar: a Bidirectional Computational Construction Grammar Framework

The proposed mechanisms for processing signed languages are integrated into the well-established FCG framework (Steels, 2011; van Trijp et al., 2022; Beuls and Van Eecke, 2023, 2025). It models language processing as a state-space search process (see Figure 4), with the initial state containing the input (form in comprehension, meaning in production) and the goal state containing an expanded structure capturing both the form and meaning of the utterance (Van Eecke et al., 2022; Van Eecke and Beuls, 2017). Between start and end states, constructions or form-meaning mappings act as operators that expand this initial state (Van Eecke et al., 2022). Representations of intermediate states within this process are commonly referred to as transient structures. The entire state-space search process is referred to as the construction application process. For more information about constructional language processing using FCG, please consult Van Eecke and Beuls (2017) and Van Eecke et al. (2022).

Within the FCG sign language module, linguistic forms are represented using our multilinear representation, while any formal semantic framework can be used to represent their meaning. Examples are procedural semantics (Woods, 1968; Woods et al., 1972; Winograd, 1972), discourse representation structure (Kamp and Reyle, 2013), and abstract/uniform meaning representation (Banarescu et al., 2013; Van Gysel et al., 2021). Like the general FCG architecture, grammars developed using the sign language package allow bidirectional processing, meaning they can be used to map form to meaning (comprehension) and meaning to form (production).

4.4 The FCG module for processing signed languages

We bundle the implemented mechanisms as an FCG module integrated into the Babel software library, allowing researchers to use and test the developed framework on their own sign language data.

The module contains several components, including methods for reading in ELAN annotation files and transforming them into the multilinear predicate notation format. A second component integrates these multilinear forms with the FCG construction application process, adding them to the initial transient structure in comprehension and extracting them from the final transient structure in production. Finally, a visualisation component integrates avatar animations and graphical repre-

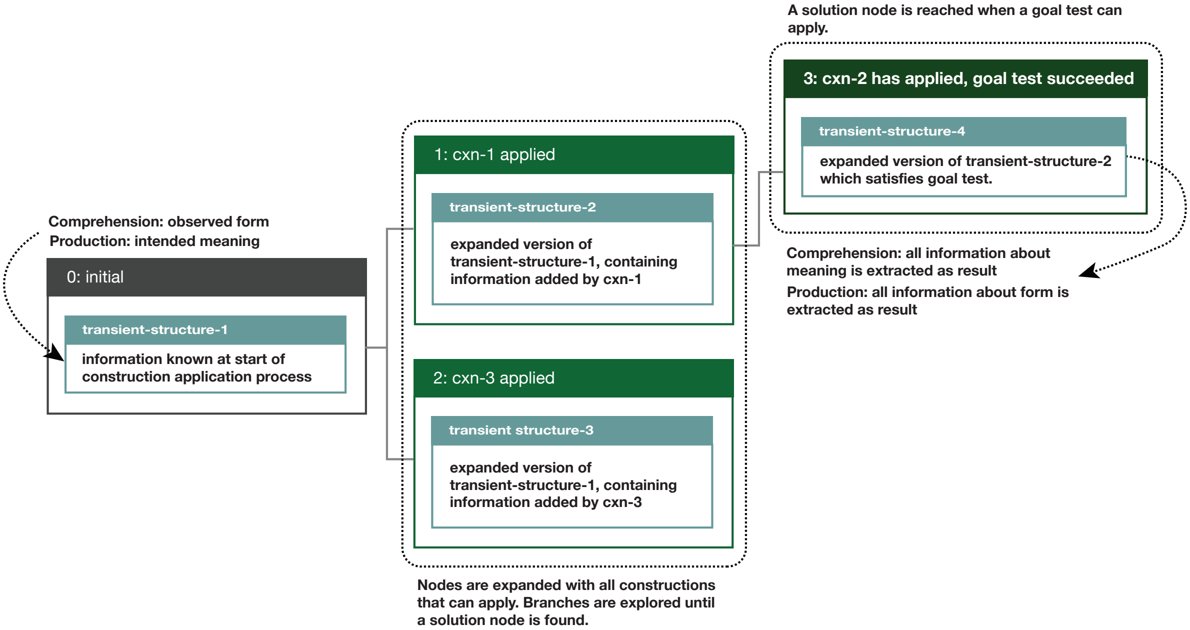

Figure 4: Illustration of the construction application process in FCG. The initial state (also referred to as initial transient structure), contains all information known at the start of processing (form in comprehension, meaning in production). Nodes are expanded by constructions and branches are explored until a solution node is reached.

sentations of multilinear structures, allowing users to inspect signed forms visually.

To use the FCG sign language processing module, a recent installation of the Babel toolkit is required (see the Babel installation page). After installing Babel and following the steps within the README of its sign language processing module, users can start using the framework.

5 Interactive Web Demonstration

To demonstrate the potential of the developed framework for the computational exploration of sign language constructions, we provide an interactive web demonstration[6] alongside this paper. It illustrates the functionality of our framework through the comprehension and production of the LSFB expression from Figure 3. The visualisations shown within the web demonstration are integrated into the FCG module for sign language processing as live visualisations, allowing users to inspect the construction application process for signed utterances in real time.

Figure 5 provides a schematic overview of the comprehension process. The initial transient structure contains the predicate notation of the observed form. Nodes in the search tree are expanded until a goal state with a complete meaning analysis is found. The transient structure of this final node contains a collection of units that were created by the applied constructions and combines information about the utterance's form and meaning. To complete the comprehension process, the meaning predicates are extracted from the final transient structure, resulting in a coherent meaning representation for the observed form.

The figure shows two constructions in detail: a concrete construction that captures the form and meaning of the LSFB sign HAUT (HAUT-CXN) and a more abstract construction which captures the typical theme-question format of questions in LSFB (THEME-QUESTION-CXN). The HAUT-CXN maps between the linguistic form (right-handed articulation with the index finger pointing upwards and performing a slight upwards movement) and the meaning of the sign HAUT (procedural meaning referring to a high point). The construction captures additional linguistic information about the sign, such as its semantic class, number, and location. The *args* feature later connects the sign's semantic arguments to those of other constructions. The THEME-QUESTION-CXN captures the information structure of LSFB questions, where the theme precedes the querying component. It enforces this precedence through an adjacency relation between the final sign of the theme and the first sign of the

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[6] Available here: `https://liesbet-devos.github.io/SL-processing-demo/`

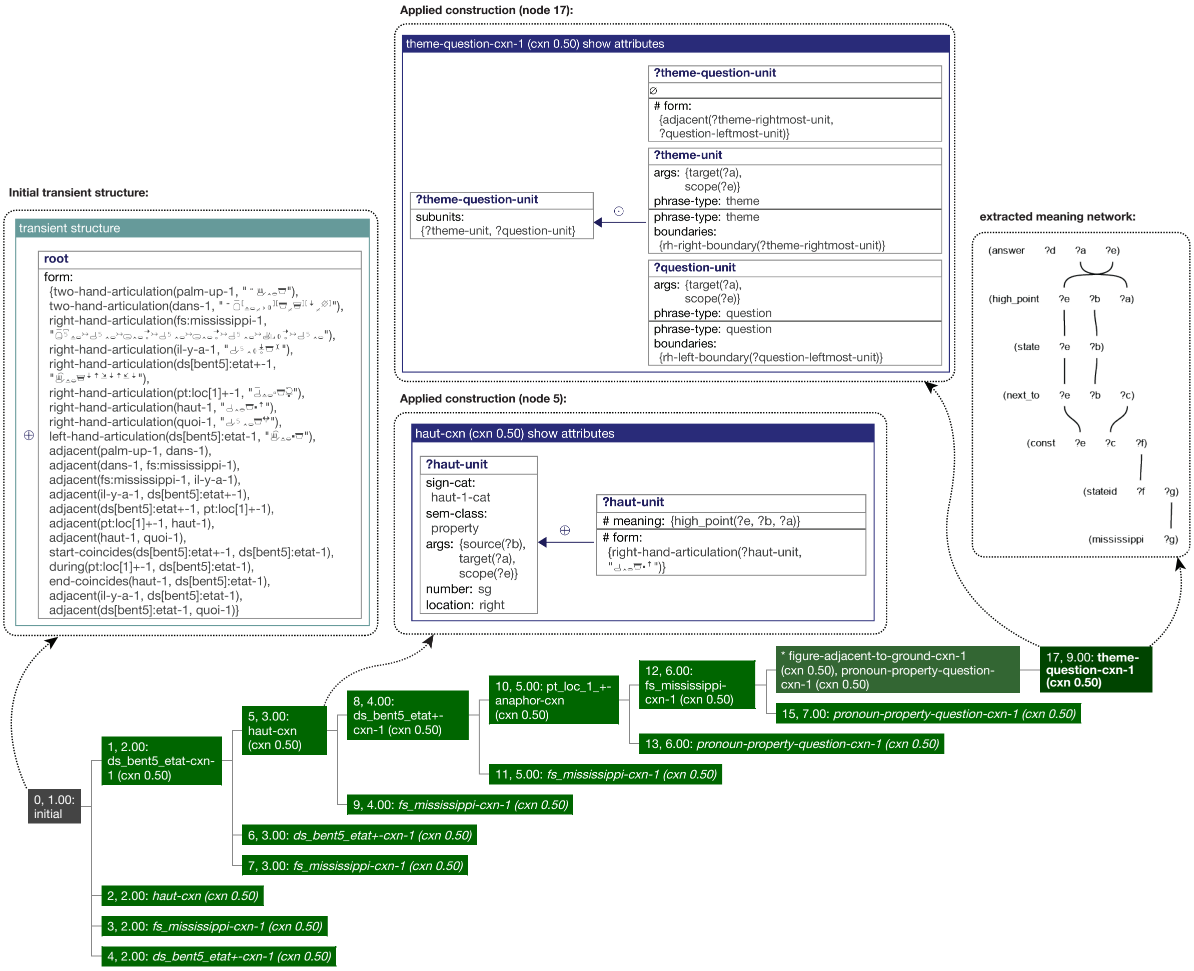

Figure 5: Schematic representation of the comprehension process for the signed expression of Figure 3. The initial transient structure contains the observed form in predicate format. A goal state is reached in node 17. To complete the comprehension process, all meaning predicates are extracted from the final transient structure, resulting in the meaning representation which is shown. During the application process, multiple constructions apply, amongst which the HAUT and THEME-QUESTION construction.

question. When this adjacency condition is met, the construction links the semantic arguments of both parts, resulting in a coherent meaning network for the expression.

This demonstration showcases how the FCG module for sign language processing facilitates comprehension and production of an LSFB expression. Its broader aim is to showcase the potential of FCG and the implemented sign language processing mechanisms for future computational exploration of sign language constructions.

6 Conclusion

The main goal of the current paper was to study and operationalize the core mechanisms required for representing and processing signed languages using computational construction grammar. We identified three core properties for the framework. It should (1) include a phonetic representation for manual signs, (2) make temporal relationships between these signs explicit, and (3) allow bidirectional processing. For phonetic representation, we rely on the well-established HamNoSys system, which describes the hand shape, orientation, location, movement and non-manual features of isolated signs. It is language-agnostic and represents signs from any sign language. While it provides the possibility to describe non-manual components as well, we do not yet include these in our approach, leaving this to future work. To describe temporal relationships between these signs, we propose a multilinear representation which extracts temporal information from ELAN annotation files. To allow bidirectional processing, we integrate the developed mechanisms into the FCG framework. The implemented mechanisms are available as a module within the Babel software library, which is openly available.

Through an interactive web-demonstration, we illustrate how the proposed mechanisms effectively represent and process the multilinear forms of a signed language. More broadly, this demonstration showcases the potential of the proposed framework for future computational exploration of sign language constructions. While it is an initial step towards a functional framework for bidirectional sign language processing, challenges remain before our approach can be scaled to large corpora and various research contexts. An example is the inclusion of non-manual components and their temporal relations.

Limitations

A considerable limitation of the presented module is its focus on manually signed forms. Non-manual features are frequent within sign language productions and play crucial roles in many sign language constructions. However, formalising these non-manual forms remains challenging, with most formal notation systems focusing primarily on manual forms. Systems like HamNoSys often include some non-manual features, but they are not as extensive and well-developed as the manual ones. Another limitation of the framework is the collection of temporal relationships, which currently does not capture differences in on- or offset time between two articulations. Such differences might be needed to capture constructions that contain non-manual features, which often have a different on- or offset time. Finally, we have only tested the module on LSFB examples. While we expect the system to apply to other sign languages, it remains to be verified empirically.

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