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Ramification of Volterra-type Rough Paths

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Yvain Bruned, Foivos Katsetsiadis

University of Edinburgh,
Email: Yvain.Bruned@ed.ac.uk, F.I.Katsetsiadis@sms.ed.ac.uk

Abstract

We extend the new approach introduced in [HT19] and [HT21] for dealing with stochastic Volterra equations using the ideas of Rough Path theory and prove global existence and uniqueness results. The main idea of this approach is simple: Instead of the iterated integrals of a path comprising the data necessary to solve any equation driven by that path, now iterated integral convolutions with the Volterra kernel comprise said data. This leads to the corresponding abstract objects called Volterra-type Rough Paths, as well as the notion of the convolution product, an extension of the natural tensor product used in Rough Path Theory.

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1 Introduction

Volterra Equations comprise a thoroughly studied class of differential equations with wide applicability in physics, engineering and other sciences, capable of adequately capturing the behavior of a wide range of natural models. Introducing stochasticity to these models via a random driving noise naturally yields the corresponding notion of Stochastic Volterra Equations. These equations are typically of the form:

\[ u(t) = u_0 + \sum_{i=0}^{d} \int_0^t k(t,r) f_i(u_r) dq_r^i, \quad u_0 \in \mathbb{R}^e \]  

(1.1)

where \( k \) is a kernel that obeys the analytic condition and is allowed to be singular in the diagonal \( t = r \), the \( f_i \) are sufficiently regular vector fields on \( \mathbb{R}^e \) and \( q \) is a stochastic process on \( \mathbb{R}^{d+1} \) such that \( q_0^r = r \). Such equations are of independent theoretical interest, but also arise in the description of the dynamics of various
natural systems and are becoming increasingly popular with the recent advent of so-called Rough Volatility Models in Mathematical Finance after the paper [GJR14], where it is empirically demonstrated that volatility is best described by a rough process. We refer the reader to Rosenbaum and coworkers in [EPR18], [ER19], [ER18], who, based on stylized facts of modern market microstructure, construct a sequence of Hawkes processes suitably rescaled in time and space that converges in law to a rough volatility model of rough Heston form with the variance process of the underlying asset obeying a stochastic Volterra Equation. Therefore, there is ample interest in developing a robust solution theory to these equations.

In cases where the noise is a Brownian Motion or a continuous semimartingale process, classical interpretations of these equations, such as the Ito interpretation by means of the classical stochastic integral are very much sufficient. Indeed, this approach has been undertaken in [OZ93] and [Zha10] where these equations are treated via the means of classical stochastic calculus. A mathematical challenge is presented when the driving noise is of wilder nature, yielding rougher realizations as its sample paths and/or appears without the semimartingale property, necessitating the search for finer interpretations of such equations. This challenge is not contained in the context of Volterra Equations, but can be seen as pertaining to a wide class of stochastic PDEs. Various tools have been introduced to tackle this problem and naturally, these tools have also been applied to yield appropriate solution theories to OoneNtaboldstyleNOoneNtaboldstyleN we shall give a brief overview of these developments that span the last three decades.

In 1998, T. Lyons introduces the Rough Path calculus in the seminal work [Ly98]. Lyons treats the problem by enhancing the process into an object known as a Rough Path, thereby introducing the higher-order calculi that allow one to obtain a “rough” formulation of the given equations. In 2004, Gubinelli introduces the concept of a controlled Rough Path in [Gub04] and later on that of a Branched Rough Path in his work [Gub10]. Advancements rapidly follow. In 2011, in one of the most impressive applications of the theory Hairer uses Rough Paths in [Hai13] to provide a solution theory to the KPZ equation, a landmark achievement in the field of singular stochastic PDEs. Shortly after, Gubinelli, Imkeller and Perkowski, in [GIP15] also introduce techniques of paracontrolled calculus in the study of singular SPDEs. Advancements culminate around the same time, when, in a major synthesis of ideas in [Hai14], Hairer develops the theory of regularity structures, being one of the first to introduce renormalization techniques in the field. This, together with the subsequent [BH19], [CH16], [BCCH21], form a body of work that covers a large class of parabolic stochastic PDEs. Finally, as an addition to the powerful arsenal developed through the theory of regularity structures, higher order paracontrolled calculus is also given in [BB19], generalising the approach developed in [GIP15].

The study of stochastic Volterra Equations follows these developments. In [DT19] and [DT11] Deya and Tindel use ideas of Rough Path theory for the treatment of non-singular Volterra equations. Furthermore, in their recent work [PT18] Prömel and Trabs treat the first order case by use of paracontrolled calculus.

As mentioned above, Regularity Structures have proven to be one of the most
potent tools for assigning a well-posed interpretation to a large class of stochastic PDEs. Indeed, a more powerful approach introduced in [BFG+20] and elaborated upon in [BFG20] has been to interpret stochastic Volterra Equations via means of the theory of Regularity Structures; this has been done down to Hölder exponent 1/3 when the driving noise is a fractional Brownian motion, with the expectation that methods therein are amenable to generalization in the case of arbitrarily low exponent. One should then be able to obtain existence and uniqueness results that are, however, only local.

In this work, we are interested in extending the approach introduced lately in [HT19] and [HT21], which is to generalize the ideas of Rough Path theory in order to treat the case of stochastic Volterra Equations. The idea is that instead of the iterated integrals of a path one now keeps track of iterated integral convolutions with the Volterra kernel. An object encoding this information is called a Volterra-type Rough Path, or simply a Volterra Path. These objects are a generalization of Branched Rough Paths and satisfy a generalization of Chen’s relation. In order to formulate this generalized relation the authors introduce a convolution product operation that serves as an extension of the natural tensor product used in Rough Path Theory.

In their works [HT19] and [HT21] the authors only treat the cases of Hölder regularity that is higher than 1/3 and 1/4 respectively. Furthermore, the Hopf-algebraic framework necessary for the description of the objects has not yet been clarified by the authors. In particular, while use of the techniques of Branched Rough Paths is attempted, the classical Connes-Kreimer Hopf algebra is not a suitable choice in the context of the results. In this work, we introduce a general framework and extend these results in the case of arbitrarily low Hölder exponent. In the process, we provide an application of a Hopf-algebraic structure that yields a robust and general description of the objects at hand. The idea for this structure is based on a plugging coproduct used in [BM20] for recovering the algebraic structures of [BH20]. It can be understood as a Connes-Kreimer type coproduct where one keeps along the edges that would normally be lost when performing an admissible cut. Making use of the ideas of Branched Rough Paths together with the more suitable framework provided by this algebraic structure, we are able to encode the convolution product on any order and to extend the main results obtained in [HT21].

We will now proceed to give a brief outline for the contents of the paper. In the next section, we begin by setting up the analytic and algebraic framework of interest by describing the analytic conditions imposed on our kernels and the ambient spaces for our objects, as well as giving a description of the Hopf algebraic structure that will be used for the description of the objects introduced. We also prove some elementary motivating propositions that hold true when one is dealing with ordinarily regular functions (see Propositions 2.6 and 2.8). Then, we move to the main objective of this section which is to introduce a convolution-type operation on our spaces of interest, which we call a convolution product and shall denote by ∗. This is done after recalling some results that were proven in [HT19] and [HT21], at which point we proceed to prove the main result of the section, which is Theorem 2.20. The statement of the theorem can be seen as giving the definition for the
convolution product operation.

This operation is vital for our description of the new objects introduced, which we shall call Branched Rough Paths of Volterra type or simply Volterra Paths. These objects, while resembling the Branched Rough Paths introduced by Gubinelli in \cite{Gubinelli}, nevertheless serve as to model rough versions of convolutional integral expressions that in general cannot be operated upon by mere tensorization and expect to yield another "integral" of the same form. We will therefore need an operation that will serve as a sort of "integral convolution" for our objects.

In the third section, we begin by giving the proper definition for a controlled Rough Path of Volterra type in Definition \ref{def:controlled} and show how to integrate these objects against a given Volterra Path in Theorem \ref{thm:integration}. We also prove a version of the "chain rule" for our Rough Path calculus (see Proposition \ref{prop:chain_rule}), showing how to lift the composition of a function \( y \) controlled by a given Volterra Path with a sufficiently regular function \( f \) into the space of controlled paths. This will allow us to finally formulate and prove our main result, which is Theorem \ref{thm:existence_and_uniqueness} on the existence and uniqueness of solutions to Rough Volterra Equations.

2 The convolution product

We begin this section by presenting the convolution product operation proposed in \cite{HT} at the level of iterated Volterra integrals and proceed to describe how it can be generalized to ramified integral expressions with tree-indexed iterations. We will use this in the next section to define the concept of a Volterra Rough Path which is an abstraction of the collection of ramified Volterra integrals corresponding to a path: it will be comprised of a sequence of functions that is \textit{stipulated} to satisfy a convolutional variant of Chen's relation. To accomplish this, we will face the challenge of defining this convolution product as an operation on the spaces these function terms reside in. This challenge has been tackled in \cite{HT} for H"older exponents \( \rho > 1/3 \). We proceed to construct a theoretical framework that is more general and works for arbitrarily low H"older exponent. Let \( T > 0 \), we denote by \( \Delta_n([0, T]) \) the subset \( \{ 0 < t_1 < \cdots < t_n < T \} \) of \( \mathbb{R}^n \) and by \( Q_n([0, T]) \) the \( n \)-th dimensional hypercube \( \{ 0 < t_i < T, i \in \{1, \ldots, n\} \} \subset \mathbb{R}^n \). We will usually omit the interval \([0, T]\) and use \( \Delta_n \) and \( Q_n \).

Let us recall the analytic condition (\textbf{H}) imposed on the kernel \( k \) in \cite{HT}. The assumption is that \( k : \Delta_2 \to \mathbb{R} \) is such that there exists \( \gamma \in (0, 1) \) so that for all \((s, r, q, \tau) \in \Delta_4 \) and \( \eta, \beta \in [0, 1] \), we have:

\begin{align}
|k(\tau, r)| & \lesssim |\tau - r|^{-\gamma} \\
|k(\tau, r) - k(q, r)| & \lesssim |q - r|^{-\gamma - \eta}|\tau - q|^\eta \\
|k(\tau, r) - k(\tau, s)| & \lesssim |\tau - r|^{-\gamma - \eta}|r - s|^\eta \\
|k(\tau, r) - k(q, r) - k(\tau, s) + k(q, s)| & \lesssim |q - r|^{-\gamma - \beta}|r - s|^\beta \\
|k(\tau, r) - k(q, r) - k(\tau, s) + k(q, s)| & \lesssim |q - r|^{-\gamma - \eta}|r - q|^\eta.
\end{align} 

(2.1)
The kernel $k$ is the basic block for the construction of iterated convolutional integrals. To represent these, we will need to introduce the appropriate algebraic structure. We first introduce a natural space of decorated rooted trees. Let $\mathcal{T}$ (resp. $\hat{\mathcal{T}}$) be the set of rooted trees with nodes decorated by $\{0, \ldots, d\}$ (resp. decorated by $\{0, \ldots, d\}$ except for the root which carries no decoration). We grade elements $\tau \in \mathcal{T}$ (resp. $\hat{\mathcal{T}}$) by the number $|\tau|$ of their nodes having a decoration and we set

$$\mathcal{T}_n := \{\tau \in \mathcal{T} : |\tau| \leq n\}, \quad n \in \mathbb{N}.$$  

We denote by $\hat{\mathcal{F}}$ (resp. $\mathcal{F}$) the set of forests, i.e. sets consisting of trees in $\hat{\mathcal{T}}$ (resp. $\mathcal{T}$). Any rooted tree $\tau \in \hat{\mathcal{T}}$, different from the empty tree $1$, can be written in terms of the $B_+^i$-operators, $i \in \{0, \ldots, d\}$ which connect the roots of the trees in a forest $\tau_1 \cdots \tau_n \in \hat{\mathcal{F}}$ to a new root decorated by $i$. Indeed, given any $\tau \in \hat{\mathcal{T}}$ other than $1$, we have that $\tau = B_+^i(\tau_1 \cdots \tau_n)$ for some $\tau_1, \ldots, \tau_n \in \hat{\mathcal{T}}$. Elements of $\mathcal{T}$ are described similarly except that we use the operator $B_+$ since their roots carry no decoration. We introduce another operator on the linear span of decorated trees denoted by $I$, which acts as follows: for $\tau \in \hat{\mathcal{T}}$, the tree $I(\tau)$ is given by grafting the root of $\tau$ onto a new root with no decoration and then decorating with $i$ the node of the new tree corresponding to the root of $\tau$. Below, we illustrate the various operations:

$$B_+^i(\cdot) = i^\nabla^j, \quad B_+^k(\cdot) = i^\nabla^j, \quad I(\cdot) = i^\nabla^j.$$

Concerning the map $|\cdot|$ which counts the decorated nodes in a tree, we have for example:

$$|i^\nabla^j| = |i^\nabla^j| = 3.$$  

A decorated tree that is of the form $I_k(\tau)$ for some $\tau \in \hat{\mathcal{T}}$ is called a planted tree. The set of these trees is denoted by $\hat{\mathcal{P}} \mathcal{F}$ and $\hat{\mathcal{P}} \mathcal{T}_n \subset \hat{\mathcal{P}} \mathcal{T}$ denotes the set of planted trees of size $n$.

**Remark 2.1** We can potentially consider a finite family of kernels $(k_i)_{i \in I}$ satisfying condition $\mathbf{H}$. Then, our decorated trees should also come equipped with edge decorations indexed by $I$. This type of structure has been introduced in the context of Regularity Structures in [BHZ19].

**Definition 2.2** Let $q$ be a path in $C^1([0, T]; \mathbb{R}^{d+1})$ and $k : \Delta_2 \rightarrow \mathbb{R}$ a Volterra kernel satisfying the analytic bounds imposed in condition $\mathbf{H}$. Let $h \in \mathcal{T}$ be a rooted tree with $n + 1$ vertices. Then, using the convention that $r_0 = \tau$, where
$q$ is the root of $h$, we define the \textit{\textit{h}th iterated Volterra integral} as a mapping $z^h : \Delta_3 \to \mathbb{R}$ given by

$$z^h_{ts}(\tau) = \int_{A^h_{ts} \subseteq \mathbb{R}^n} \prod_{(i,j) \in E^h} k(r_i, r_j) \prod_{\ell \in N^h} dq^h_{r_{\ell}}$$

where $i_{\ell}$ is the decoration attached to the node $\ell$ and the domain of integration is the set

$$A^h_{ts} = \bigcap_{(i,j) \in E^h} \{ t > r_i > r_j > s \}$$

i.e. the order relations defining the variable ranges are directly given by the partial ordering induced by the tree $h$. Let $V \subset \mathbb{R}^h$ be of cardinality $m$. Then, we also define:

$$z^h_{ts}(\tau) = \prod_{w \in V} \hat{q}^i_{r_{\ell}} \int_{A^h_{ts}(\tau) \subseteq \mathbb{R}^e-m} \prod_{(i,j) \in E^h} k(r_i, r_j) \prod_{\ell \in N^h \backslash V} dq^h_{r_{\ell}}$$

where $A^h_{ts}(\tau) \subseteq \mathbb{R}^n$ corresponds to $A^h_{ts}$ when one fixes the values of $(r_\ell)_{\ell \in V}$.

\textbf{Example 2.3 (Linearly Iterated Volterra Integrals)} Let $h$ be the ladder tree with $n$ vertices, with decorations $i_1, \ldots, i_n$. Then, the \textit{iterated Volterra integral} of order $n$ is a mapping $z^h : \Delta_3 \to \mathbb{R}$ given by

$$(s, t, \tau) \mapsto z^h_{ts}(\tau) = \int_{t > r_n > \ldots > r_1 > s} k(\tau, r_n) \prod_{j=1}^{n-1} k(r_j+1, r_j) dq^i_{r_1} \ldots dq^i_{r_n}.$$

This expression corresponds to the Volterra-type Rough Paths as they were originally introduced in [HT19].

Before stating Proposition 2.6 which presents the convolution in the smooth case, we introduce some notation. We consider the following plugging coproduct $\Delta : \mathcal{H} \to \mathcal{H} \otimes \mathcal{H}$ and the coaction $\hat{\Delta} : \hat{\mathcal{H}} \to \hat{\mathcal{H}} \otimes \mathcal{H}$ that are defined recursively as follows:

$$\Delta B^+(h_1 \cdot \ldots \cdot h_n) = \sum_{I \subseteq \{1, \ldots, n\}} B^+(\cdot) \otimes B^+\left(\prod_{i \in I} h_i\right) \hat{\Delta} \prod_{\{1, \ldots, n\} \backslash I} h_i.$$  

(2.2)

$$\hat{\Delta} B^+(h_1 \cdot \ldots \cdot h_n) = \sum_{I \subseteq \{1, \ldots, n\}} B^+(\cdot) \otimes B^\wedge\left(\prod_{i \in I} h_i\right) \hat{\Delta} \prod_{i \in \{1, \ldots, n\} \backslash I} h_i.$$  

Alternatively, one can describe the coproduct by using the concept of admissible cuts:

$$\Delta h = h \otimes 1 + \sum_{c \in \text{Adm}(h)} R^c(h) \otimes \hat{P}^c(h).$$
where $\text{Adm}(h)$ is the set of admissible cuts, which are defined as collections of edges with the property that any path from the root to a leaf contains at most one edge of the collection. We denote by $P^c(h)$ the pruned forest that is formed by collecting all the edges at or above the cut, including the ones upon which the cut was performed, so that the edges that were attached to the same node in $h$ are part of the same tree. The term $R^c(h)$ corresponds to the "trunk", that is the subforest formed by the edges under the ones upon which the cut was performed. This coproduct differs from the classical Butcher-Connes-Kreimer coproduct \cite{But72,CK08}. It can also be constructed via a plugging pre-Lie product, see \cite[Sec 3.3]{BM20}. To illustrate with an example, we compute the result below for a given tree:

$$
\Delta \left[ k^{ij} \ell \right] = k^{ij} \otimes 1 + 1 \otimes k^{ij} \ell + k^i \otimes \ell^j + k^j \otimes \ell^i + k^i \otimes j^j.
$$

Using Sweedler’s notation for the coproduct of a forest $h$, we will write:

$$\Delta h = \sum_{\langle h \rangle} h^{(1)} \otimes h^{(2)}.$$

In the sequel, we use an extension of the map $\Delta$ by identifying the nodes. We will consider the nodes of $h^{(1)}$ and $h^{(2)}$ as a subset of those of $h$. Therefore, the roots of the trees in $h^{(2)}$ will be identified with some nodes in $h^{(1)}$. This property is crucial in order to define a convolution operation on tree-indexed iterated integrals. We also define the reduced coproduct $\hat{\Delta}$ as follows:

$$\hat{\Delta} h = \Delta h - h \otimes 1 - 1 \otimes h = \sum_{\langle h \rangle} h^{(1)} \otimes h^{(2)}.$$

While the coproduct $\Delta$ introduced is slightly different from the original Connes-Kreimer coproduct, one has a projection of the algebra $\mathcal{H}$ onto the classical algebra of forests that intertwines their actions. Hence, while the the coproduct $\Delta$ carries slightly more information, one has a "forgetful" morphism onto the original Connes-Kreimer Hopf algebra. To be specific, we define the operator $B_-$ as the left inverse of $B_+$. Then $B_-$ is an algebra morphism from $\mathcal{F}$ to $\mathcal{F}$ when these are equipped with the corresponding forest products and given $\Delta_{\text{CK}}$, the Connes-Kreimer coproduct, one has

$$\Delta_{\text{CK}}B_-, \quad (\text{id} \otimes B_-)\Delta = \hat{\Delta}_{\text{CK}}B_- \quad \text{(2.4)}$$
where
\[
\Delta_{ck}h_1 \cdot \ldots \cdot h_n = \sum_{I \subseteq \{1, \ldots, n\}} \left( \text{id} \otimes \prod_{i \in I} h_i \right) \hat{\Delta} \prod_{i \in \{1, \ldots, n\} \setminus I} h_i.
\]

\[
\hat{\Delta}_{ck}B^k_+(h_1 \cdot \ldots \cdot h_n) = \sum_{I \subseteq \{1, \ldots, n\}} \left( B^k_+(\cdot) \otimes \prod_{i \in I} h_i \right) \hat{\Delta} \prod_{i \in \{1, \ldots, n\} \setminus I} h_i.
\]

Indeed, by applying $B_-$ to (2.2),

\[
(B_- \otimes B_-)\Delta B_+(h_1 \cdot \ldots \cdot h_n) = \sum_{I \subseteq \{1, \ldots, n\}} \left( \text{id} \otimes \prod_{i \in I} h_i \right) \hat{\Delta} \prod_{i \in \{1, \ldots, n\} \setminus I} h_i.
\]

Using an inductive argument, one can show (2.4) by using (2.6) and (2.7). Before introducing the convolution operation, we extend Definition 2.2 to forests.

**Definition 2.4** Let $h = h_1 \cdot \ldots \cdot h_n$ a forest, we define the $h$ - th iterated Volterra integral as:

\[
\mathcal{Z}_{ts}^{h_{\tau_1, \ldots, \tau_n}} = \prod_{i=1}^n \mathcal{Z}_{ts}^{h_i_{\tau_i}}
\]

where $\tau_1, \ldots, \tau_n \in [s, t]$. The function $(\tau_1, \ldots, \tau_n) \mapsto \prod_{i=1}^n \mathcal{Z}_{ts}^{h_i_{\tau_i}}$ is obtained by tensorising the $\mathcal{Z}_{ts}^{h_i_{\tau_i}}$.

**Remark 2.5** Definition 2.4 is the reason why we have introduced the spaces $\mathcal{T}$ and $\mathcal{F}$. Elements of $\mathcal{T}$ can be seen as forests and in that case one could see the elements of $\mathcal{F}$ as "forests of forests". Indeed, we have a bijection between trees in $\mathcal{T}$ and forests in $\mathcal{F}$. Given a tree $h \in \mathcal{T}$, one just needs to remove the root and the edges adjacent to it in order to obtain a forest. Below, we illustrate this bijection:

\[
\begin{array}{c}
\begin{array}{c}
\tau \downarrow \tau \\
\vdots \\
\tau \\
\end{array}
\end{array}
\leftrightarrow
\begin{array}{c}
\begin{array}{c}
\tau \downarrow \tau \\
\vdots \\
\tau \\
\end{array}
\end{array}
\]

where $\tau_1, \ldots, \tau_n \in [s, t]$. The function $(\tau_1, \ldots, \tau_n) \mapsto \prod_{i=1}^n \mathcal{Z}_{ts}^{h_i_{\tau_i}}$ is obtained by tensorising the $\mathcal{Z}_{ts}^{h_i_{\tau_i}}$. Indeed, we have a bijection between trees in $\mathcal{T}$ and forests in $\mathcal{F}$. Given a tree $h \in \mathcal{T}$, one just needs to remove the root and the edges adjacent to it in order to obtain a forest. Below, we illustrate this bijection: 
The use of the spaces $\mathcal{T}$ and $\mathcal{F}$ is robust to the introduction of decorations on the edges. This structure is also reminiscent of the one used in [BS20] for dispersive equations, where a planted tree is associated to a frequency and planted trees with the same frequency can been seen as a tree.

As mentioned, these integrals satisfy a generalized Chen identity. We prove this below.

**Proposition 2.6** Let $h$ be a tree in $\mathcal{T}$ and $(s, u, t, \tau) \in \Delta_4$, we have

$$z_{ts}^h = \sum_{(h)} z_{tu}^{h(1), \tau} \ast z_{us}^{h(2)},$$

(2.8)

where the convolution product $\ast$ is defined as follows

$$z_{tu}^{h(1), \tau} \ast z_{us}^{h(2)} := \int_{\mathbb{R}^m} z_{tu}^{h(1), \tau}((r_i)_{i \in V}) \prod_{i \in V} z_{us}^{h(2), r_i} dr_i$$

Here, $V \subset N_h$ is of cardinality $m$ and is such that every $i \in V$ considered as a node of $h$ appears also as a root of a tree $h_i^{(2)}$ in $h^{(2)}$ and $h^{(2)} = \prod_{i \in V} h_i^{(2)}$.

**Proof.** Let $h$ be a tree with $n + 1$ vertices. Using the convention that $\rho = \tau$ where $\rho$ is the root of $h$, we have

$$z_{ts}^h = \int_{A^h_t \subseteq \mathbb{R}^n} \prod_{(i,j) \in E_h} k(r_i, r_j) \prod_{\ell \in N_h} dq_{\ell}^{\ell}$$

Let $u \in [s, t]$, then one notices that

$$A^h_t = \bigcup_{C \in \text{Adm}(h)} \bigcap_{(i,j) \in E_h} \bigcap_{(k,l) \in C} \{r_k > u > r_l\} \cap \{t > r_1 > r_j > s\}$$

All unions in the above expression are pairwise disjoint and therefore,

$$z_{ts}^h = \sum_{C \in \text{Adm}(h)} \int_{A^h_t \subseteq \mathbb{R}^n} \prod_{(i,j) \in E_h} k(r_i, r_j) \prod_{\ell \in N_h} dq_{\ell}^{\ell}$$

where $A_{ts}^{C, h}(u)$ is defined as follows:

$$A_{ts}^{C, h}(u) = \bigcap_{(i,j) \in E_h} \bigcap_{(k,l) \in C} \{r_k > u > r_l\} \cap \{t > r_1 > r_j > s\}$$

(2.9)

If $h^{(1)} = R_C(h)$ and $h^{(2)} = \tilde{P}_C(h)$, then one has:

$$A_{ts}^{C, h}(u) = A_{tu}^{h^{(1)}} \times A_{us}^{h^{(2)}}.$$
Then, we can rewrite (2.9) as

\[
A_{t,s}^{C,h}(u) = \left( \bigcap_{(i,j) \in E_{h(1)}} \{ t > r_i > r_j > u \} \right) \times \left( \bigcap_{(i,j) \in E_{h(2)}} \{ u > r_i > r_j > s \} \right)
\]

where the sets intersected in the right hand side are each considered as a subset of an appropriate subspace of \( \mathbb{R}^n \). We conclude by using Fubini.

\[\square\]

**Example 2.7** If \( h \) is the ladder tree with \( n \) vertices decorated by \( i_1, \ldots, i_n \), we have for \( t > r_1 > s \):

\[
zh_{t,s}^{h,\tau}(r_1) = \int_{t > r_n > \ldots > r_2 > r_1} k(\tau, r_n) \prod_{j=1}^{n-1} k(r_{j+1}, r_j) \hat{q}_{r_1}^{i_1} dq_{r_2}^{i_2} \ldots dq_{r_n}^{i_n}
\]

In similar spirit, in the case of \( h \) being a linear tree, we get a simpler version of Chen’s relation closer to the one for classical Rough Paths. Proposition 2.6 reduces to

\[
zh_{t,s}^{n,\tau} = \sum_{i=0}^{n} z_{t,u}^{n-i,\tau} \ast z_{u,s}^{i}
\]

when \( n \) corresponds to the linear tree with the set of nodes decorations to be of cardinal one. From this relation we can recover the classical Chen’s relation for the signature of a path with bounded variation, since the convolution product reduces to the tensor product by choosing a trivial kernel.

Our aim now is to capture the algebraic properties of these generalized signatures in order to abstract from them the definition of a Branched Rough Path of Volterra-type. With this in mind, we prove the following proposition, which describes the convolution product in terms that can be generalized in the rough setting. The idea is that we can then use an expression similar to the one below as a definition for the convolution product in the rough case.

**Proposition 2.8** Let \( h \) be a tree with \( n \) decorated vertices. Let \( f_s : \mathbb{R}^n \to \mathbb{R}^e \) be a smooth function whose arguments are indexed by \( N_h \cdot (\tau_{i})_{i} \in N_h \mapsto f_s^{(\tau_{i})}_{i} \in \mathbb{R}^e \). Then, the following identity holds:

\[
z_{t,s}^{h,\tau} \ast f_s = \lim_{|\mathcal{P}| \to 0} \sum_{[u,v] \in \mathcal{P}} \sum_{(h)} z_{t,u}^{n-1,\tau} \ast (z_{u,s}^{(1)} \ast (z_{t,s}^{(2)} \ast f_s))
\]  

**Proof.** Let \( h \) be a tree with \( n + 1 \) vertices. The proof follows the same lines as the one for Proposition 2.6. Now, fix any partition \( \mathcal{P} = \{ u_1, \ldots, u_n \} \) of the interval \([s, t]\) and notice that

\[
A_{t,s}^{h} = \bigcup_{[u,v] \in \mathcal{P}} \bigcap_{C \in \text{Adm}(h)} \bigcap_{(i,j) \in E_h} \bigcap_{(k,l) \in C} \{ v > r_1 \} \cap \{ r_k > u > r_j \} \cap \{ t > r_i > r_j > s \}
\]
All unions in the above expression are pairwise disjoint and therefore,

\[
\begin{align*}
\mathbf{z}^h_{ts} &= \sum_{[u,v] \in \mathcal{P}} \sum_{C \in \text{Adm}(h)} \int A^h_{ts}(v,u) \subseteq \mathbb{R}^n \prod_{(i,j) \in h} k(r_i, r_j) \prod_{t \in N_h} dq^i_t
\end{align*}
\]

where the set \( A^h_{ts}(v,u) \) is defined as follows:

\[
A^h_{ts}(v,u) = \bigcap_{(i,j) \in E_s(k,l) \in C} \{ v > r_1 \} \cap \{ r_k > u > r_1 \} \cap \{ t > r_i > r_j > s \}
\]

Thus, since the above decomposition of \( A^h_{ts} \) is true for any partition \( \mathcal{P} \) of \([s,t] \), we can split each set \( A^h_{ts}(v,u) \) into a Cartesian product and use Fubini’s theorem to obtain the equality

\[
\mathbf{z}^h_{ts} * f_s = \lim_{|\mathcal{P}| \to 0} \sum_{[u,v] \in \mathcal{P}} \sum_{(h)} \mathbf{z}^{(1)}_{vu} * (\mathbf{z}^{(2)}_{ts} * f_s)
\]

which is precisely the desired identity. This concludes the proof.

We now wish to extend this product operation in the rough setting. In order to do this, we will need a version of the Sewing Lemma different from the one used in classical Rough Path Theory. We will call it the Volterra Sewing Lemma, following the terminology used in [HT10]. We first introduce the spaces needed for the formulation of this lemma. We recall [HT21 Def. 2.3].

**Definition 2.9** Let \((\alpha, \gamma) \in [0,1]^2\) with \( \varrho = \alpha - \gamma > 0 \), we define the following space \( \mathcal{V}^{(\alpha,\gamma)}(\Delta_2; \mathbb{R}) \) of functions \( z \) such that \( z^T_0 = z_0 \in \mathbb{R} \) and equipped with the norm:

\[
\| z \|_{(\alpha,\gamma),1} = |z_0| + \| z \|_{(\alpha,\gamma),1} + \| z \|_{(\alpha,\gamma),1,2}
\]

where

\[
\| z \|_{(\alpha,\gamma),1} = \sup_{(s,t,\tau) \in \Delta_3} |\tau - t|^{-\gamma} |t - s|^{\alpha} \wedge |\tau - s|^{\varrho}
\]

\[
\| z \|_{(\alpha,\gamma),1,2} = \sup_{(s,t,\tau,\tau') \in \Delta_4} \frac{|z^T_{st\tau'}|}{|\tau - t'|^{\eta} |\tau' - t|^{-\eta + \xi}(|\tau' - t|^{-\gamma - \xi} |t - s|^{\alpha} \wedge |\tau' - s|^{\varrho - \xi})}
\]

Given \( \alpha \) and \( \gamma \) in \([0,1]\) we also define the norm for elements \( \omega \) of the \( k \)-fold tensor product \( \bigotimes_{i=1}^{k} \mathcal{V}^{(\alpha,\gamma)} \) to be the projective tensor norm

\[
\| \omega \|_{(\alpha,\gamma)} = \inf \left\{ \sum \| z^1 \| \cdots \| z^k \| : \omega = \sum z^1 \otimes \cdots \otimes z^k \right\}
\]

where the infimum is taken over all decompositions of \( \omega \). This defines a crossnorm, in the sense that

\[
\| z^1 \otimes \cdots \otimes z^k \|_{(\alpha,\gamma)} = \| z^1 \|_{(\alpha,\gamma)} \cdots \| z^k \|_{(\alpha,\gamma)}
\]

We denote the completion of the algebraic tensor product with respect to this norm by \( \bigotimes_{i=1}^{k} \mathcal{V}^{(\alpha,\gamma)} \).
**Definition 2.10** For any \( u \in \mathbb{R} \) and any Banach space \( V \) we define the operator \( \delta_u : C(\Delta_2; V) \rightarrow C(\Delta_3; V) \) as follows:

\[
\delta_u f_{ts} = f_{ts} - f_{tu} - f_{us}.
\]

We now introduce the space of abstract integrands that is needed to formulate the Volterra Sewing Lemma, as given in [HT21 Def. 2.9].

**Definition 2.11** Let \( \alpha \in (0, 1) \) and \( \gamma \in (0, 1) \) with \( \alpha - \gamma > 0 \). We suppose given three coefficients \( (\beta, \kappa, \theta) \), with \( (\kappa + \theta) \in (0, 1) \) and \( \beta \in (1, \infty) \). Denote by \( \Psi'(\alpha, \gamma)(\beta, \kappa, \theta)(\Delta_4; \mathbb{R}^d) \), the space of all functions of the form \( \Delta_4 \ni (v, s, t, \tau) \mapsto (\Xi_v^\Delta)_{ts} \in \mathbb{R}^d \) such that the following norm is finite:

\[
\| \Xi \|_{\Psi'(\alpha, \gamma)(\beta, \kappa, \theta)} = \| \Xi \|_{(\alpha, \gamma)} + \| \delta \Xi \|_{(\beta, \kappa, \theta)}.
\]  (2.11)

In equation (2.11), the operator \( \delta \) is the one introduced above and the term \( \| \delta \Xi \|_{(\beta, \kappa, \theta)} \) takes the double singularity into account. Namely, we define

\[
\| \delta \Xi \|_{(\beta, \kappa, \theta), 1} = \| \delta \Xi \|_{(\beta, \kappa, \theta), 1} + \| \delta \Xi \|_{(\beta, \kappa, \theta), 1, 2};
\]

where

\[
\| \delta \Xi \|_{(\beta, \kappa, \theta), 1} := \sup_{(v, s, m, t, \tau) \in \Delta_5} \left| \delta_m(\Xi_v^\Delta)_{ts} \right|^{\kappa} |t - s|^{-\kappa} |s - v|^{-\theta} \wedge |t - v|^{\beta - \kappa - \theta},
\]

and the term \( \| \delta \Xi \|_{(\beta, \kappa, \theta), 1, 2} \) is defined by

\[
\| \delta \Xi \|_{(\beta, \kappa, \theta), 1, 2} := \sup_{(v, s, m, t, \tau, \tau') \in \Delta_6} \frac{\left| \delta_m(\Xi_v^{\tau'})_{ts} \right|}{f(v, s, t, \tau', \tau)},
\]

where the function \( f \) is given by

\[
f(v, s, t, \tau', \tau) = |\tau - \tau'|^\eta |\tau' - t|^{-\eta + \zeta} (|\tau' - t|^{-\kappa - \zeta} |t - s|^{\beta} |s - v|^{-\theta} \wedge |\tau' - v|^{\beta - \kappa - \theta - \zeta}).
\]  (2.14)

Notice that we will use \( \Psi'(\alpha, \gamma)(\beta, \kappa, \theta) \) as a space of abstract Volterra integrands with a double singularity.

We are now ready to state the Volterra Sewing Lemma with two singularities (see [HT21 Lem. 3.2]).

**Lemma 2.12 (Volterra Sewing Lemma)** We consider the following exponents \( (\alpha, \gamma) \), and \( (\beta, \kappa, \theta) \), with \( \beta \in (1, \infty) \), \( (\kappa + \theta) \in (0, 1) \), \( \alpha \in (0, 1) \) and \( \gamma \in (0, 1) \) such that \( \alpha - \gamma > 0 \). Let \( \Psi'(\alpha, \gamma)(\beta, \kappa, \theta) \) and \( \Psi'(\alpha, \gamma) \) be the spaces given in Definition 2.11 and Definition 2.9, respectively. Then, there exists a linear continuous map \( \mathcal{F} : \Psi'(\alpha, \gamma)(\beta, \kappa, \theta)(\Delta_4; \mathbb{R}^d) \rightarrow \Psi'(\alpha, \gamma)(\Delta_3; \mathbb{R}^d) \) such that the following hold true.
(i) The quantity
\[ \mathcal{F}(\Xi^\nu)^{ts} := \lim_{|\mathcal{P}| \to 0} \sum_{[u,w] \in \mathcal{P}} (\Xi^\nu)_{wu} \]
exists for all \((v, s, t, \tau) \in \Delta_4\), where \(\mathcal{P}\) is a generic partition of \([s, t]\) and \(|\mathcal{P}|\)
denotes the mesh size of the partition. Furthermore, we define \(\mathcal{F}(\Xi^\nu)^{ts} := \mathcal{F}(\Xi^\nu)^{t0} - \mathcal{F}(\Xi^\nu)^{s0}\).

(ii) For all \((v, s, t, \tau) \in \Delta_4\) we have
\[ |\mathcal{F}(\Xi^\nu)^{ts} - (\Xi^\nu)^{ts}| \lesssim \|\delta \Xi\|_{(\beta, \kappa, \theta), 1, 1} \left( |t - t' - \kappa|^{-\kappa} |t - s|^{-\theta} \wedge |t - v|^{\beta - \kappa - \theta} \right), \]
while for \((v, s, t, \tau', \tau) \in \Delta_5\) we get
\[ |\mathcal{F}(\Xi^{\tau\tau'})^{ts} - (\Xi^{\tau\tau'})^{ts}| \lesssim \|\delta \Xi\|_{(\beta, \kappa, \theta), 1, 2} f(v, s, t, \tau', \tau), \]
where \(f\) is the function given by \((2.14)\).

A next step now is to find the right spaces on which to define the \(*\) operation so that we may abstract from the notion of a collection of iterated Volterra integrals that of a Volterra-type Rough Path. However, even with the appropriate abstract function spaces at hand, the definition of the product will still pose a challenge: defining the resulting expression in terms of the kernels involved as one big iterated integral is conceptually straightforward but our functions are indeed expressible as such integrals; but defining the product on an abstract function space in a way that generalizes these cases of interest is a delicate matter, as we shall see. We begin by giving the definition of the convolution product for increments. We recall \(\text{[HT19]}\) Thm. 26:

**Proposition 2.13** Let \(z \in \mathcal{W}^{(\alpha, \gamma)}(\Delta_2, \mathbb{R})\) and \(y \in \mathcal{W}^{(\alpha, \gamma)}(\Delta_2, \mathbb{R}^c)\). We set \(\varrho = \alpha - \gamma\) and assume that \(\varrho > 0\). Then, we define the convolution product between \(z\) and \(y\) as:
\[ z^w_{tu} \ast y^w_{us} := \lim_{|\mathcal{P}| \to 0} \sum_{[u', v'] \in \mathcal{P}} z^w_{u'u'} y^w_{uv'} \]
where \((s, t, u, \tau) \in \Delta_4\). Moreover, one gets the following inequalities:
\[ |z^w_{tu} \ast y^w_{us}| \lesssim \|z\|_{(\alpha, \gamma), 1} \|y\|_{(\alpha, \gamma), 1, 2} \left( |t - t' - \gamma| \wedge |t - s|^{2\varrho + \gamma} \right) \wedge |\tau - t|^{2\varrho} \wedge |\tau - s|^{2\varrho + \gamma} \]
\[ |z^\tau_{tu} \ast y^\tau_{us}| \lesssim \|z\|_{(\alpha, \gamma), 1, 2} \|y\|_{(\alpha, \gamma), 1, 2} |\tau' - \tau|^{\gamma} |\tau - t|^{-\gamma + \zeta} \left( |t - t' - \gamma| \wedge |t - s|^{2\varrho + \gamma} \wedge |\tau - t|^{2\varrho + \gamma} \right) \]
where \(\eta \in [0, 1], \zeta \in [0, 2\varrho]\) and \((s, u, t, \tau, \tau') \in \Delta_5\).

We need to extend the convolution \(\ast\) to \(y\) with more variables.
We define the space $\mathcal{V}_n^{(\alpha, \gamma)}(Q_{n+1}, \mathbb{R}^e)$ to be the space of functions $y : Q_{n+1} \to \mathbb{R}^e$ such that $y_0^{r_1, \ldots, r_n} = y_0$ and

$$|||y|||_{(\alpha, \gamma), n} = \sum_{k=1}^{n} |||y|||_{(\alpha, \gamma), n, k} < \infty$$

where, for every $k \leq n$, we define the norms

$$|||y|||_{(\alpha, \gamma), n, k} = \sup_{(s, t, r_1, \ldots, r_n, r_{n+1}) \in Q_{n+3}} \frac{|y_{ts}^{r_1, \ldots, r_n} - y_{ts}^{r_1, \ldots, r_n, r_{n+1}}|}{h_{\eta, \zeta}(s, t, r_1, \ldots, r_n)}$$

where

$$h_{\eta, \zeta}(s, t, r_1, \ldots, r_n) = |r - u|^{-\gamma} \min(r_1, \ldots, r, u, \ldots, r_n) - t^{-\eta+\zeta} \times \left( \min(r_1, \ldots, r, u, \ldots, r_n) - t^{-\eta} \right) \wedge \min(r_1, \ldots, r, u, \ldots, r_n) - s^{(\alpha - \gamma - \zeta)}.$$ 

Here, the values $r$ and $u$ appearing as superscripts in the expression for the numerator are the values of the $k$-th variable of $y$.

**Remark 2.15** Note that the constituent norms introduced above are similar to the norm $||| \cdot |||_{(\alpha, \gamma), 1, 2}$

**Definition 2.16** Let $\alpha, \gamma \in (0, 1)$ with $\alpha - \gamma > 0$ and $n \leq 1/\alpha$ be fixed. We define a tree-indexed family of spaces recursively by first setting

$$\mathcal{V}_1^{(\alpha, \gamma)} := \mathcal{V}^{(\alpha, \gamma)}$$

We then define for any $h \in \mathcal{F}$ with $|h| \leq n \leq 1/\alpha$ the space $\mathcal{V}^{h, \alpha, \gamma} \subset \mathcal{V}^{(|h|+\gamma, \gamma)}$ consisting of all $z^h \in \mathcal{V}^{(|h|+\gamma, \gamma)}$ such that

$$\delta_u z^h_{ts} = \sum_{(h')} z^{(1)}_{tu} \ast z^{(2)}_{us}$$

for some functions

$$z^{(1)} \in \mathcal{V}^{h^{(1)}, \alpha, \gamma}, \quad z^{(2)} \in \bigcup_{k=1}^{m} \left( \mathcal{V}^{h^{(2)}, \alpha, \gamma} \right)^{\otimes k}$$

with $m = |h^{(2)}|$ and such that, for every $y \in \mathcal{V}_n^{(\alpha, \gamma)}$, one has

$$\delta_u z^h_{ts} \ast y_s = \sum_{(h')} \left( z^{(1)}_{tu} \ast \left( z^{(2)}_{us} \ast y_s \right) \right)$$

where the $\ast$ operation on $\mathcal{V}^{1, \alpha, \gamma}$ has already been defined and given $h \in \mathcal{H}$ we assume that the operation has already been defined for trees of order up to $|h| - 1$. This can be done inductively via Theorem 2.20 and Proposition 2.13. The identity (2.10) is used for the construction of $\ast$ in Theorem 2.20.
Remark 2.17 The spaces $\mathcal{Y}^{h,\alpha,\gamma}$ are metric subspaces of the corresponding $\mathcal{Y}^{(\lfloor h \rfloor \omega,\gamma,\gamma)}$ space. However, they do not appear to be linear subspaces.

Remark 2.18 The identity (2.16) can be viewed as an extension of the Chen’s relation where the terms $z_{s}^{h}$ are considered as operators. This property appears in the smooth case, as can be seen by the proof of Proposition 2.8.

Remark 2.19 Note that, the definition of the spaces $\mathcal{Y}^{(\lfloor h \rfloor \omega,\gamma,\gamma)}$ in (2.16) can only be considered in tandem with that of the * operation as given by Theorem 2.20. The two are intertwined in a spirally recursive formulation.

Theorem 2.20 Let $h$ be a tree in $\mathcal{T}_{n}$ and let $z^{h} \in \mathcal{Y}^{h,\alpha,\gamma}$ and $y \in \mathcal{Y}^{(\alpha,\gamma)}$ with $\alpha, \gamma \in (0,1)$ and $\omega = \alpha - \gamma > 0$. Then, for all fixed $(s, t, \tau) \in \Delta_{3}$ the expression

$$z_{ts}^{h,\tau} * y_{s} := \lim_{|\varphi| \to 0} \sum_{(u, v) \in \mathcal{P}} z_{vu}^{h,\tau} \otimes y_{s}^{u} \cdots \cdots + \sum_{(h)} z_{vu}^{(1)} \tau * (z_{vs}^{(2)} \tau * y_{s})$$

yields a well-defined Volterra-Young integral. It follows that * is a well defined operation between the three-parameter Volterra function $z^{h}$ and an $|h|\omega$-parameter path $y$, linear in it’s second argument. Moreover, we have the following two inequalities:

$$|z_{ts}^{h,\tau} * (y_{s}^{u} \cdots \cdots - y_{s}^{u} \cdots \cdots)| \lesssim \left( \sum_{(h)} \prod_{i=1}^{k} ||z_{vu}^{(i)}||_{(|h|\omega)\omega,\alpha,\gamma} \right)$$

(2.16)

$$|z_{ts}^{h,\tau'} \tau' \tau * (y_{s}^{u} \cdots \cdots - y_{s}^{u} \cdots \cdots)| \lesssim \left( \sum_{(h)} \prod_{i=1}^{k} ||z_{vu}^{(i)}||_{(|h|\omega)\omega,\alpha,\gamma} \right)$$

(2.17)

In these bounds, our notation of summing over $(h)$ means that the summation is over all elements $h^{(1)} \otimes \cdots \otimes h^{(k)}$ that appear in the expansion of $h = \sum_{k} \Delta^{k} h$, $\Delta^{i+1} = (1 \otimes \Delta^{i}) \Delta$, $\Delta^{0} = \text{id}$.

Proof. We shall induct on the number of vertices of the tree $h$. The base case of $h \in \mathcal{T}_{1}$ is covered by Proposition 2.13. We now assume that the statement holds for all $h \in \mathcal{T}_{p-1}$ and proceed to prove it is true for $h \in \mathcal{T}_{p}$ with $p \leq n$.

Step 1: Let us denote by $\mathcal{F}_{\omega}$ the approximation of the right hand side above, that is

$$\mathcal{F}_{\omega} := \sum_{(u, v) \in \mathcal{P}} \Xi_{vu}^{h,\tau} := \sum_{(u, v) \in \mathcal{P}} z_{vu}^{h,\tau} \otimes y_{s}^{u} + \delta_{u} z_{vu}^{h,\tau} \star y_{s}^{u} \cdots \cdots.$$  

(2.18)
Our goal is to apply Lemma [2.12] to the increment Ξ. We must therefore check the regularity of the integrand under the action of δ. To this aim, two simple computations using that \(\delta_r z^{h,\tau}_{vu} = \sum_{(h')} z^{h(1)}_{vr} \ast z^{h(2)}_{ru} \) reveal

\[
\delta_r (z^{h,\tau}_{vu} \otimes y^u_s) = -z^{h,\tau}_{vr} \otimes (y^r_s - y^u_s) + \sum_{(h')} z^{h(1)}_{vr} \ast z^{h(2)}_{ru} \otimes y^u_s, \tag{2.19}
\]

\[
\delta_r ((\delta_u z^{h,\tau}_{vu}) \ast y_s) = -\sum_{(h')} z^{h(1)}_{vr} \ast (z^{h(2)}_{ru} \ast y_s), \tag{2.20}
\]

To prove (2.20) we first expand the right hand side of the identity using the definition of the operator \(\delta_r\) and get

\[
\delta_r (z^{h,\tau}_{vu} \ast y_s) = \sum_{(h')} (z^{h(1)}_{vu} \ast (z^{h(2)}_{us} \ast y_s)) - (z^{h(1)}_{vr} \ast (z^{h(2)}_{us} \ast y_s))
\]

\[
- (z^{h(1)}_{ru} \ast (z^{h(2)}_{us} \ast y_s))
\]

We know by Chen’s relation, that one has

\[
z^{h(1)}_{vu} = \sum_{(h)} z^{h(1)}_{vr} \ast z^{h(2)}_{ru}
\]

Therefore,

\[
z^{h(1)}_{vu} \ast (z^{h(2)}_{us} \ast y_s) - z^{h(1)}_{ru} \ast (z^{h(2)}_{us} \ast y_s) = \sum_{(h), (h(1)) \neq 1} (z^{h(1)}_{vr} \ast z^{h(2)}_{ru}) \ast (z^{h(2)}_{us} \ast y_s)
\]

Similarly, one has

\[
z^{h(1)}_{vr} \ast (z^{h(2)}_{rs} \ast y_s) = \sum_{(h)} z^{h(1)}_{vr} \ast ((z^{h(2)}_{ru} \ast z^{h(2)}_{us}) \ast y_s)
\]

One can see that \(h(1) \neq 1\) and \(h(2) \neq 1\) which is not the case for the range of \(h(22)\) in the sum above. Now, after making these substitutions in the original sum, by coassociativity of the coproduct and (2.16) we see that most of the terms possess a counterpart with identical forest-indices and opposite sign. These terms cancel out and we eventually obtain (2.20).

**Step 2:** Let us now analyze the regularity of the terms in (2.19)-(2.20), starting with the right hand side of (2.19). Namely, we recall our assumption that \(z^h \in \mathcal{Y}^r((h)|\varphi+\gamma,\gamma)\). We have also assumed that \(||y||_{(|\alpha,\gamma),|h|} < \infty\). We can therefore multiply the bounds afforded by the finite norms of \(z^h\) and \(y\) and use the fact that \(u \leq r \leq v\) to obtain the following bound:

\[
|z^{h,\tau}_{vu} \otimes (y^u_s - y^r_s)| \lesssim ||y||_{(|\alpha,\gamma),|h|} ||z^h||_{(|\varphi+\gamma,\gamma),1} \times |u-s|^{-\eta}|r-v|^{-\gamma}|v-u|^{-|h|\varphi+\gamma+\eta}, \tag{2.21}
\]
We then choose \( \eta \in [0, 1] \) such that \( |h| \varrho + \gamma + \eta > 1 \), which is always possible since \( \varrho > 0 \).

**Step 3:** In order to treat the remaining terms in (2.19) and (2.20), observe that formula (2.18) trivially yields (recall again that \( y_s^n \) has to be considered as a constant in the lower variable)

\[
z^{h, \tau}_{ts} \ast y_s = z^{h, \tau}_{ts} \otimes y_s.
\]

Therefore, we can gather our two remaining terms into

\[
\sum_{(h)} z^{(1)}_{vr} \ast z^{(2)}_{ru} \otimes y_s^{u_1, \ldots, u_r} - \sum_{(h)} z^{(1)}_{vr} \ast z^{(2)}_{ru} \ast y_s = \sum_{(h)} z^{(1)}_{vr} \ast z^{(2)}_{ru} \ast (y_s^{u_1, \ldots, u_r} - y_s)
\]

We introduce the following notation for \( y \) and \( h_1 \) a subforest of \( h \): \( \tilde{y}_s^{h_1, r} \), which means that \( y_s \) is evaluated at \( r \) for all the variables corresponding to the nodes of \( h_1 \). The other variables are free. If the nodes of \( h_1 \) receive the evaluation \( r_1, \ldots, r_{|h_1|} \), we use the notation \( \tilde{y}_s^{h_1, r_1, \ldots, r_{|h_1|}} \). Now, using the inequality in the statement of this theorem, which is assumed to hold for \( h \in \mathcal{F}_{p-1} \) by our inductive hypothesis (see Proposition 2.13 for the base case) and using that \( |||y|||_{(\alpha, \gamma), |h|} < \infty \) we get

\[
|z^{(1)}_{vr} \ast z^{(2)}_{ru} | \cdot (\tilde{y}_s^{h, u} - y_s) | \lesssim \left( \sum_{(\nu^{(1)})} \prod_{i=1}^k |z^{(1)}_{nu} |_{(\nu^{(1)})}^{(1)} |(\nu^{(1)})_{(\varrho + \gamma, \gamma)} \right) \times |||w|||_{(\alpha, \gamma), |h^{(1)}|}
\times \left| |\tau - v| - \gamma |v - r|^{|h|_{\varrho + \gamma}} \wedge |\tau - r|^{|h|_{\varrho}} \right|
\]

where \( w_{ru}^{\tau_1, r_{|h^{(1)}|}} = z^{(2)}_{ru} \ast (\tilde{y}_s^{h, u} - y_s^{h_1, r_1, \ldots, r_{|h^{(1)}|}}). \) In the last inequality we simply used that \(|v - r| \leq |v - u|\) and \(|\tau - r| \leq |\tau - u|\) since \( v \geq r \geq u \). Next, we want to bound \( |||w|||_{(\alpha, \gamma), |h^{(1)}|} \). We have

\[
|||w|||_{(\alpha, \gamma), |h^{(1)}|} \lesssim \left| \prod_{(\nu^{(2)})} |z^{(2)}_{nu} |_{(\nu^{(2)})}^{(2)} |(\nu^{(2)})_{(\varrho + \gamma, \gamma)} \right| |y|_{(\alpha, \gamma), |h^{(1)}|} |v - u|^{|\varrho|} |u - s|^{-\eta}
\]

where we have repeatedly applied the bound (2.17) since in the expression for \( w \) the factors comprising the term \( z^{(2)}_{nu} \) are convolved with respect to different variables of \( y_s^{u} - y_s^{h_1, r_1, \ldots, r_{|h^{(1)}|}} \). This yields a bound that involves the product of the norms of the factors comprising \( z^{(2)}_{nu} \), which, if \( z^{(2)}_{nu} \) is seen as an element of a tensor power of \( \mathcal{F}^{(\alpha, \gamma)} \), is equal to the factor \( |||z^{(2)}_{nu} |_{(\nu^{(2)})_{(\varrho + \gamma, \gamma)} \rangle \rangle \) appearing in the inequality above by virtue of Definition 2.9. Thus, combining the above estimates we get...
\[
\sum \left( \sum \prod_{i=1}^{k} \|z^{(i)}\|_{(\|h^{(i)}\|_{\varrho+\gamma,\gamma})} \right) \|z^{(2)}\|_{(\|h^{(2)}\|_{\varrho+\gamma,\gamma})} = \sum \prod_{i=1}^{k} \|z^{(i)}\|_{(\|h^{(i)}\|_{\varrho+\gamma,\gamma})}.
\]

where we have used the fact that

\[
\sum (\sum \prod_{i=1}^{k} \|z^{(i)}\|_{(\|h^{(i)}\|_{\varrho+\gamma,\gamma})}) = \sum \prod_{i=1}^{k} \|z^{(i)}\|_{(\|h^{(i)}\|_{\varrho+\gamma,\gamma})}.
\]

We notice that the regularity obtained in this last inequality is the same as for (2.21). Hence, choosing \( \eta \in [0, 1] \) as after (2.21) and recalling (2.19) and (2.20), we obtain that

\[
|\delta_{\tau} z^{\tau}_{s} | \lesssim c_{y,z} |\tau - v|^{-\gamma} |u - s|^{-\eta} |v - u|^{\|h\|_{\varrho+\gamma,\gamma}}
\]

where \( \mu = \|h\|_{\varrho+\gamma,\gamma} > 1 \) and where the constant \( c_{y,z} \) in this inequality is the same as that in the right hand side of the last inequality above it.

Using this bound one can readily check that \( \|\delta_{\tau} z^{\tau}_{s} \|_{(\|h\|_{\varrho+\gamma,\gamma}),1} < \infty \). One can similarly check that \( \|\delta_{\tau} z^{\tau}_{s} \|_{(\|h\|_{\varrho+\gamma,\gamma}),1} < \infty \). Therefore, using the Volterra Sewing Lemma with two singularities (Lemma 2.12), we get that the Riemann sums defined by (2.18) converge as \( |\mathcal{E}| \to 0 \), and we define

\[
z^{h,\tau}_{s} \ast y_{s} := \lim_{|\mathcal{E}| \to 0} J_{\mathcal{E}}.
\]

We also immediately obtain the two bounds afforded to us by the Volterra Sewing Lemma, thus proving the inequalities (2.16) and (2.17) in the statement of the theorem. This completes the proof.

\[\square\]

3 Rough Volterra Equations

In this section, our aim is to prove the main theorem on existence and uniqueness of solutions to Rough Volterra Equations with driving noise of arbitrarily low Hölder exponent. We begin by giving the definition of a Volterra-type Rough Path. We then go on to define the concept of a controlled Volterra Path. As in the classical Branched Rough Path setting, the latter will comprise the class of paths that can be integrated against a given Volterra-type Rough Path.

**Definition 3.1** Fix \( \alpha, \gamma \in (0, 1) \) with \( \alpha - \gamma > 0 \) be fixed. Let \( (z_{i})_{i \in \{0,...,d\}} \) such that \( z_{i} \in \mathcal{F}^{(\alpha,\gamma)}(\Delta_{2}, \mathbb{R}) \). For \( n \) with \( (n+1)\varrho + \gamma > 1 \), we suppose given a tree-indexed family of iterated integrals \( (z^{\tau, h}_{i})_{h \leq n} \) indexed by the trees of \( \mathcal{F} \) such that

\[
z^{\tau, h}_{i} = z_{i}, \quad e_{i} = i.
\]
and one has:

$$\delta_u z_{ts}^{\tau,h} = \sum_{(h)'} z_{tu}^{(1)} \ast z_{us}^{(2)}$$

(3.1)

where the Sweedler’s notation corresponds to the reduced coproduct $\hat{\Delta}$. Let $h$ be a tree with $m \leq n$ nodes. We suppose that for every $y \in \mathcal{Y}_m^{(\alpha,\gamma)}$, one has:

$$\delta_u z_{ts}^{h,\tau} \ast y_s = \sum_{(h)'} \left( z_{tu}^{(1)} \ast \left( z_{us}^{(2)} \ast y_s \right) \right)$$

where the product $\ast$ is defined inductively via Theorem [2.20] and Proposition [2.13]. We also assume that $z^h \in \mathcal{Y}_m^{(h,\rho,\gamma,\gamma)}$. We then say that $z$ is a Volterra Branched Rough Path. We define the norm $\| \cdot \|_{(\alpha,\gamma)}$ as:

$$\|z\|_{(\alpha,\gamma)} = \sum_{h \in \mathcal{T}_n} \|z^h\|_{(h,\rho,\gamma,\gamma)}$$

**Definition 3.2 (Controlled Volterra Path)** Let $z$ be an $\alpha$-Hölder Volterra Branched Rough Path and let $n = \lfloor 1/\alpha \rfloor$. A Volterra Branched Rough Path controlled by $z$ is a function $y = (y^h)_{h \in \mathcal{T}_{n-1}}$ such that, for every $h \in \mathcal{T}_{n-1}$ we have $y^h \in \mathcal{Y}_m^{(\alpha,\gamma)}(Q_{|h|+1}, R^e)$ and the remainder terms, for every $\tau \in [s,t]$,

$$R^h_{ts} = y^h_{ts} - \sum_{\varrho \in \mathcal{T}_{n-1}} \sum_{\sigma \in \mathcal{T}_{n-1}} c(\sigma, h, \varrho) z^\varrho_{ts} \ast y^\sigma_s$$

(3.2)

satisfy $R^h \in \mathcal{Y}_m^{(n-|h|\alpha, (n-|h|)\gamma)}$. Here $c(\sigma, h, \varrho)$ is the counting function for the number of appearances of the term $h \otimes \varrho$ in the expansion of the reduced coproduct $\hat{\Delta} \sigma$. The space of such functions is called the space of Controlled Volterra Branched Rough Paths. We equip it with the norm

$$\|y\|_{z,(\alpha,\gamma)} = \sum_{h \in \mathcal{T}_{n-1}} \left( |y^0| + \|y^h\|_{(\alpha,\gamma)} + \|R^h\|_{(n-|h|)\alpha, (n-|h|)\gamma)} \right)$$

We shall use $\mathcal{D}_z^{(\alpha,\gamma)}$ to denote the space of $(\alpha, \gamma)$-Hölder Volterra Branched Paths controlled by $z$. If $y$ is zero on trees which are not planted and $y^h$ is a function of $|h|$ variables not depending on the variable associated to the root of $h$, we denote this space as $\hat{\mathcal{D}}_z^{(\alpha,\gamma)}$. We define $\mathcal{D}_z^{(\alpha,\gamma)}$ as the following affine space:

$$\mathcal{D}_z^{(\alpha,\gamma)} = \{ y \in \mathcal{D}_z^{(\alpha,\gamma)} | y^0 = (y^0_{0,\ldots,\tau})_{h \in \mathcal{T}_{n-1}} = (y^0_{0,\ldots,\tau})_{h \in \mathcal{T}_{n-1}} \}$$

**Remark 3.3** We shall consider a controlled path $\mathcal{Y}$ as defined on the hypercube $Q_n$. It is possible to refine this domain of definition to a set of the form $\bigcap_{\text{ord}(h)} \{ t_i < t_j \} \subset Q_{|h|+1}$ where the order relations imposed on the components is given directly by the partial ordering induced by the tree $h$. We choose to work on $Q_n$ for the sake of simplicity.
Rough Volterra Equations

We will now show how one can integrate a controlled path against a given Volterra-type Rough Path. This will in essence be done by applying a formal "shift" on the Taylor-like approximation to the object $Y$. In the case of Terry Lyons's rough paths this is done by using the shift operator on the tensor algebra of words indexing the expansion. In our case the role of the shift operator is played by a "grafting" operator $\mathcal{F}$ from the tensor algebra of forests to the tensor algebra of trees. We formulate the rough integration theorem below:

**Theorem 3.4** Let $q \in \mathcal{C}^\alpha$ and $k$ be a Volterra kernel satisfying the analytic bounds (2.7). Define $z_t^{\tau,r} = \int_0^t k(\tau, r) dq_r^\tau$ and assume there exists a Branched Volterra Rough Path $z$ of order $p$ built from Definition [3,7]. Additionally, suppose that the $p$ components of $z$ are uniformly bounded. We now consider a controlled Volterra path $(y^h)_{h \in \mathcal{T}_{p-1}} \in \mathfrak{D}^{(\alpha, \gamma)}_z$. Then, one has:

(i) The following limit exists for all $(s, t, \tau) \in \Delta_3$,

$$w^\tau_{ts} = \int_s^t k(\tau, r) y^\tau_r dq^\tau_r := \lim_{\|\mathcal{P}\| \to 0} \sum_{[u, v] \in \mathcal{P}} \sum_{h \in \mathcal{T}_{p-1}} z^{\tau(h), \tau}_u \ast y^h_v. \quad (3.3)$$

(ii) One has the following bounds for all $(s, t, p, q) \in \Delta_4$, $\eta \in [0, 1]$ and $\zeta \in [0, pq]$

$$|w^\tau_{ts} - \Xi^\tau_{ts}| \lesssim \|y\|_{\mathcal{I}_{(\alpha, \gamma)}}(1 + \|z\|_{(\alpha, \gamma)})^p \left(||\tau - t||^{-\gamma}|t - s|^{p\gamma + \gamma} \wedge |\tau - s|^{p\gamma}\right) \quad (3.4)$$

$$|w^{\tau p}_{ts} - \Xi^{\tau p}_{ts}| \lesssim \|y\|_{\mathcal{I}_{(\alpha, \gamma)}}(1 + \|z\|_{(\alpha, \gamma)})^p |p - q^n| |q - t|^{-\eta + \zeta} \left(||q - t||^{-\gamma - \zeta}|t - s|^{p\gamma + \gamma} \wedge |q - s|^{p\gamma - \zeta}\right) \quad (3.5)$$

(iv) The tuple $(w^h)_{h \in \mathcal{T}_{p-1}}$ is a controlled Volterra path in $\mathfrak{D}^{(\alpha, \gamma)}_z$ where $w^\tau_{1s} = y^h_1$, $w^h_i = 0$ for $h$ not a planted tree and $w^\tau_{i1} = \mathcal{F}(\Xi)_{h}$. The proof of Theorem 3.4 is as follows:

$$\Xi^\tau_{vu} = \sum_{h \in \mathcal{T}_{p-1}} z^{\tau(h), \tau}_u \ast y^h_v,$$

where $z^{\tau(h), \tau}_u \ast y^h_v$ is understood according to Theorem 2.20. Indeed, $(y^h)_{h \in \mathcal{T}_{p-1}} \in \mathcal{D}^{(\alpha, \gamma)}_z$ implies that $y^h \in \mathcal{D}^{(\alpha, \gamma)}_{|h|+1}$. Since $\Xi$ is clearly well-defined, our next step is to invoke the Volterra Sewing Lemma 2.12 in order to define

$$w^\tau_{ts} = \int_s^t k(\tau, r) y^\tau_r dq^\tau_r = \mathcal{F}(\Xi)_{hs}.$$

To this aim, similarly to the proof of Theorem 2.20, we need to check that $\delta \Xi$ is sufficiently regular. This is what we proceed to do below. Combining (2.11) and (2.16), we get the following relation for $(u, m, v, \tau) \in \Delta_4$,

$$\delta_w \Xi^\tau_{vu} = \sum_{h \in \mathcal{T}_{p-1}} \left( z^{\tau(h), \tau}_u \ast y^h_v - z^{\tau(h), \tau}_u \ast y^h_m - z^{\tau(h), \tau}_m \ast y^h_u \right)$$
This completes the proof. Now, we resort to the fact that $y$ is a controlled Volterra Branched Rough Path and thus satisfies the local approximation (3.2). Substituting the appropriate expression in place of $y^h$ then allows us to write:

$$z_{vm}^{\alpha,\beta} \star y_{m\mu}^h = \sum_{\rho \in \mathcal{P}_{\mu-1}} \sum_{\sigma \in \mathcal{P}_{\rho-1}} c(\rho, h, \sigma) z_{vm}^{\alpha,\beta} \star (z_{m\mu}^\rho \star y_{\mu}^\sigma) + z_{vm}^{\alpha,\beta} \star R_{m\mu}^h$$

Plugging this into the expression we have obtained for $\delta \Xi$ we get

$$\delta_{m} \Xi_{vu} = \sum_{h \in \mathcal{P}_{\rho-1}} \left( \sum_{\sigma \in \mathcal{P}_{\rho-1}} (z_{vm}^{\alpha,\beta} \star z_{m\mu}^h) \star y_{m\mu}^h \right) - \sum_{\rho \in \mathcal{P}_{\mu-1}} \sum_{\sigma \in \mathcal{P}_{\rho-1}} c(\rho, h, \sigma) z_{vm}^{\alpha,\beta} \star (z_{m\mu}^\rho \star y_{\mu}^\sigma) - \sum_{h \in \mathcal{P}_{\rho-1}} z_{vm}^{\alpha,\beta} \star R_{m\mu}^h$$

Using (2.16), the terms should almost cancel each other out leaving only those of highest order, whose regularity we will have to analyse. Therefore, we get

$$\delta_{m} \Xi_{vu} = \sum_{h \in \mathcal{P}_{\rho-1}} z_{vm}^{\alpha,\beta} \star y_{m\mu}^h - \sum_{h \in \mathcal{P}_{\rho-1}} z_{vm}^{\alpha,\beta} \star R_{m\mu}^h$$

Using this expression, we can now analyze the regularity of $\delta \Xi$. Indeed, invoking Theorem 2.20 we get for all $h \in \mathcal{P}_{\rho-1} \setminus \mathcal{P}_{\rho-2}$ the following inequalities:

$$\left| z_{vm}^{\alpha,\beta} \star y_{m\mu}^h \right| \lesssim \left| y^h \right|_{((p-1)q+\gamma, \gamma)} \left( 1 + \left| z \right| \right) \left| u - m \right|^{p-\gamma} \left| v - m \right|^{p+\gamma} \left| \tau - v \right| \left| v - m \right|^{(p+1)q+\gamma}$$

Recalling that $\tau > v > m > u$, we thus obtain that

$$\left| \delta_{m} \Xi_{vu} \right| \lesssim C_{y,z} \cdot \left| \tau - v \right| \left| v - u \right|^{(p+1)q+\gamma}.$$

Since $(p+1) \cdot q + \gamma > 1$, we can apply the Volterra Sewing Lemma 2.12 to define $w_{t}\Xi := \mathcal{F}(\Xi)_{t \cdot}$ and at the same time obtain the bounds needed for parts (ii) and (iii) of the theorem. For the last point, the bound (3.4) guarantees that $w_{t}^{\alpha,\beta}$ has the correct Taylor expansion and is a controlled Volterra rough path with $w_{t}^{\alpha,\beta} = y_{t}^{h}$. This completes the proof.

The next step is to show how we can lift the composition of a controlled rough path $y$ with a sufficiently regular function $f$ in the space $\mathcal{D}_{x}^{(\alpha,\beta)}$ of controlled Volterra Equations.
Rough Volterra Equations

Paths. This will finally allow us to formulate our equation abstractly in the Rough Path sense.

The following theorem shows that if \( f \) is a sufficiently smooth function and \( y \) is a controlled path of Volterra-type, then \( f(y) \) may also be seen as a controlled path. It also gives us the form of the higher-order Gubinelli derivatives of \( f(y) \). It’s role is directly analogous to that of the chain rule in differential calculus.

**Proposition 3.5** Let \( f \in \mathcal{C}^p_b(\mathbb{R}^c) \) and assume \((y^h)_{h \in \mathcal{T}_{p-1}} \in \mathcal{D}_x^{(\alpha,\gamma)}(\mathbb{R}^c)\). Then the composition \((f(y^h))_{h \in \mathcal{T}_{p-1}} \) is a controlled Branched Volterra Rough Path in \( \mathcal{D}_x^{(\alpha,\gamma)}(\mathbb{R}^c) \) and it’s Gubinelli derivatives are given for \( h = \prod_{i=1}^m h_i \in \mathcal{T}_{p-1} \) by

\[
f(y^h) = \prod_{i=1}^m S(h_i) \frac{D^m f(y^h)}{m! S(h)} y_s^h \otimes \cdots \otimes y_s^m,
\]

where \( S(h) \) is the symmetry factor associated to \( h \) and \( \prod_{i=1}^m h_i \) is the tree product of the planted trees \( h_i \). Moreover, one has

\[
\|f(y)\|_{\mathbb{Z},(\alpha,\gamma)} \lesssim \left( 1 + \|y\|_{\mathbb{Z},(\alpha,\gamma)} \right)^{p-1} \times 
\left[ \left( \sum_{h \in \mathcal{T}_{p-1}} |y^h_0| + \|y\|_{\mathbb{Z},(\alpha,\gamma)} \right) \vee \left( \sum_{h \in \mathcal{T}_{p-1}} |y^h_0| + \|y\|_{\mathbb{Z},(\alpha,\gamma)} \right) \right]^{p-1}.
\]

**Proof.** From (3.2), we get

\[
y_s^h = \sum_{\sigma \in \mathcal{T}_{p-1}} \sum_{\tau \in \mathcal{T}_{p-1}} c(\sigma, h, \varrho) z_s^\sigma \ast y_s^\tau + R_s^h
\]

Using Taylor’s theorem, we obtain:

\[
f(y^h) - f(y^h_0) = \sum_{h = \prod_{i=1}^m h_i \in \mathcal{T}_{p-1}} \prod_{i=1}^m S(h_i) \frac{D^m f(y^h_0)}{m!} \prod_{i=1}^m z_s^h_i \ast y_s^h_i
\]

where the remainder \( R_s^h \) is given by

\[
\tilde{R}_s^h = \sum_{m=1}^{p-1} \frac{D^m f(y^h_0)}{m!} \left( \sum_{h = \prod_{i=1}^m h_i \in \mathcal{T}_{p-1}} \prod_{i=1}^m S(h_i) \left( \prod_{i=1}^m z_s^h_i \ast y_s^h_i \right)^{m-\tau} (R_s^h)^{\tau} \right)
\]

\[+ \sum_{h = \prod_{i=1}^m h_i \in \mathcal{T}_{p-1}} \prod_{i=1}^m S(h_i) \prod_{i=1}^m z_s^h_i \ast y_s^h_i \]
\[
\frac{(y_0^m)^{m+1}}{m!} \int_0^1 (1 - \theta)^m f^{(m+1)}(\theta y_t^\tau + (1 - \theta)y_s^\tau))d\theta.
\]

By bounding each term of the previous sum, one can easily check that \( R \in C^{(p\alpha, p\gamma)} \).

Let \( h = \prod_{i=1}^m h_i \in \mathfrak{T}_{p-1} \), then one has

\[
f(y_I^{h_1}) - f(y_I^{h_2}) \approx \sum_{i=1}^m \frac{1}{m!} D^m f(y_I^{h_i}) y_s^{h_i} \otimes \ldots \otimes y_s^{h_m} + \frac{1}{m!} D^m f(y_I^{h_i}) y_I^{h_1} \otimes \ldots \otimes y_I^{h_1} \otimes (y_I^{h_1} - y_I^{h_i}) \otimes \ldots \otimes y_I^{h_m}.
\]

Then, one has to plug the expansions \( (3.9) \) and \( (3.8) \) in order to conclude. This completes the proof.

**Example 3.6** We consider, as an example, the special case of Proposition 3.5 with \( p = 3 \). Then, one has the following forests:

\[
h_1 = i^{1}, \quad h_2 = j^{1}, \quad h_3 = i^{\sqrt{j}}, \quad h_4 = i^{\sqrt[j]{j}}.
\]

We then obtain the corresponding Gubinelli derivatives:

\[
f(y_I^{h_1}) = f'(y_I^{h_1}) y_I^{h_1}, \quad f(y_I^{h_2}) = f''(y_I^{h_2}) y_I^{h_2}, \quad f(y_I^{h_4}) = f'(y_I^{h_4}) y_I^{h_4}.
\]

Before formulating our main theorem, we introduce some new spaces. Let \( 0 \leq a \leq b \leq T \), we consider

\[
\Delta_T^{(a, b)} = \{(s, \tau) \in [a, b] \times [0, T] | a \leq s \leq \tau \leq T \}.
\]

The main theorem for existence and uniqueness of solutions to Rough Volterra Equations is then formulated as follows:

**Theorem 3.7** Let \( z \in C^{(\alpha, \gamma)}(\mathbb{R}) \). Assume that \( z \) satisfies the same hypothesis as in Theorem 3.4 and suppose that \( f_i \in C_0^{\infty}(\mathbb{R}^d) \) for \( i \in \{0, \ldots, d\} \). Then, there exists a unique Volterra solution in \( \mathcal{D}_T^{(\alpha, \gamma)}(\mathbb{R}^d) \) to the equation

\[
y_t = y_0 + \sum_{i=0}^d \int_0^t k(\tau, r) f_i(y_r^\tau) dq_\tau^{i} \quad t \in [0, T], \quad y_0 \in \mathbb{R}^d
\]

where the integrals above are understood as rough Volterra integrals in the sense of Theorem 3.4.

**Proof.** We begin by defining:

\[
(\Xi_t^h)_{h \in \mathfrak{T}_{p-1}} := (f_i(y_t^h))_{h \in \mathfrak{T}_{p-1}} \in \mathcal{D}_T^{(p\alpha + \gamma, \gamma)}
\]
as given by Proposition 3.5. Restricting to a subinterval \([0, T]\), Theorem 3.4 allows us to define the map

\[ \mathcal{M}_T \left( (y^h_{t})_{h \in \mathcal{T}_{p-1}} \right) = \left( \Xi_t^h, \tau \right)_{h \in \mathcal{T}_{p-1}}, \quad (t, \tau) \in \Delta_2^T ([0, T]) \]

where

\[ \Xi_t^h = y_0 + \sum_{i=0}^{d} \int_0^t k(\tau, r) \Xi_t^r, \quad \Xi_t^h = 0, \quad h \notin \mathcal{T}_{p-1}. \]

The solution of our Rough Volterra Equation (3.10) on \([0, T]\) will be constructed as a fixed point of the map \(\mathcal{M}_T\). We consider a parameter \(\beta\) such that \(\beta \leq \alpha\) and \(\beta - \gamma \geq \frac{1}{p-1}\).

**Step 1.** We begin by defining the unit ball

\[ \mathcal{B}_T = \{ (y^h_{t})_{h \in \mathcal{T}_{p-1}} \in \mathcal{D}_{\mathcal{T}, \beta, \gamma} (\Delta_2^T ([0, T]); \mathbb{R}^m) : ||(y^h_{t})_{h \in \mathcal{T}_{p-1}}||_{(\alpha, \gamma)} \leq 1 \} \]

We will assume from now on that \(||z||_{(\alpha, \gamma)}[0,T] = M\). We consider

\[ w_{ts}^r = (w_{ts}^h, r)_{h \in \mathcal{T}_{p-1}} = \mathcal{M}_T \left( (y^h_{t})_{h \in \mathcal{T}_{p-1}} \right)_{ts} \]

Then, by a simple extension of inequalities 3.4 and 3.5 for \(y \in \mathcal{D}_{\mathcal{T}, \beta, \gamma}\) we have:

\[ ||w_{ts}^r|| \leq \sum_{i=0}^{d} \sum_{h \in \mathcal{T}_{p-1}} |z^r_{i,t} | f_i(y^h_{t}) + \]

\[ + ||f_i(y)||_{(\alpha, \gamma)} (1 + ||z||_{(\beta, \gamma)})p-1 |p - q| + |q - t|^\gamma + \zeta \]

\[ |(q - t)|^{-\gamma - \zeta} |t - s|^{(p+1)\gamma + \zeta} \]

Then, using inequality 2.17 we have, for some constant \(C\) depending only on \(M, \alpha, \gamma\) and \(||f||_{\mathcal{L}^{p+1}}\) that

\[ ||\mathcal{M}_T((y^h_{t})_{h \in \mathcal{T}_{p-1}})||_{(\alpha, \gamma)} \leq \sum_{i=0}^{d} C ||z^r_{i,t} ||_{(\beta, \gamma)} p^{-2} \]

\[ + ||f_i(y)||_{(\alpha, \gamma)} ||z||_{(\alpha, \gamma)} (1 + ||z||_{(\beta, \gamma)})p-2 T^{\alpha - \beta}. \]

Hence, by inequality 3.7 one obtains

\[ ||\mathcal{M}_T((y^h_{t})_{h \in \mathcal{T}_{p-1}})||_{(\alpha, \gamma)} \leq C ||z||_{(\alpha, \gamma)} (1 + ||z||_{(\beta, \gamma)})^{2p-3} \times \]

\[ \left( \sum_{h \in \mathcal{T}_{p-1}} |y^h_{0}| + ||y||_{(\alpha, \gamma)} \right) \vee \left( \sum_{h \in \mathcal{T}_{p-1}} |y^h_{0}| + ||y||_{(\alpha, \gamma)} \right)^{p-1}. T^{\alpha - \beta}. \]
Then, under the additional assumption that \( y \in \mathcal{B}_T \), we obtain a bound of the form
\[
|\mathcal{M}_T((y^h)_{h \in \mathcal{T}_{p-1}})|_{\mathcal{L}(\beta, \gamma)} \leq c \cdot T^{\alpha - \beta}
\]
Hence, for \( T \) small enough, the ball \( \mathcal{B}_T \) is left invariant.

**Step 2.** Next, we will prove that \( \mathcal{M}_T \) is a contraction on \( \mathcal{D}_2^{(\alpha, \gamma)} \). To this aim, we set \( F_i = f_i(y) - f_i(\bar{y}) \) and consider the controlled path \( F = (F^h)_{h \in \mathcal{T}_{p-1}} \in \mathcal{D}_2^{(\beta, \gamma)} \).

Now, using
\[
|||\mathcal{M}_T((y^h)_{h \in \mathcal{T}_{p-1}}) - \mathcal{M}_T((\bar{y}^h)_{h \in \mathcal{T}_{p-1}})|||_{\mathcal{L}(\alpha, \gamma)} \leq \sum_{i=0}^d (1 + |||z|||_{(\alpha, \gamma)})^{p-1} \times

|||F^h_i|||_{(\beta, \gamma)} T^{\alpha - \beta} + |||(\bar{F}^h_i)_{h \in \mathcal{T}_{p-1}}|||_{\mathcal{L}(\beta, \gamma)} (1 + |||z|||_{(\alpha, \gamma)})^{p-1} T^{\alpha - \beta}
\]
Next, we will need to find a bound for \( |||(F^h_i)_{h \in \mathcal{T}_{p-1}}|||_{\mathcal{L}(\beta, \gamma)} \) with respect to \( |||(y^h - \bar{y}^h)_{h \in \mathcal{T}_{p-1}}|||_{\mathcal{L}(\beta, \gamma)} \). Recalling that \( F_i = f_i(y) - f_i(\bar{y}) \) and keeping in mind the form of the Gubinelli derivatives using the "chain rule" (Theorem 3.5) we proved earlier, we can obtain such a bound using an approach similar to that in [PH14]. That is, taking into account that \( y \) and \( \bar{y} \) are both in the ball \( \mathcal{B}_T \) and since we have assumed that \( |||z|||_{(\alpha, \gamma)} \leq M \), one can check that there exists a constant \( C'' = C_{M, \alpha, \gamma, ||f||_{\mathcal{B}_T}^p} \)

such that
\[
||(F^h_i)_{h \in \mathcal{T}_{p-1}}|||_{\mathcal{L}(\beta, \gamma)} \leq C'' |||(y^h - \bar{y}^h)_{h \in \mathcal{T}_{p-1}}|||_{\mathcal{L}(\beta, \gamma)}
\]

Therefore, combining this inequality with the previous one we get that
\[
|||\mathcal{M}_T\left((y^h - \bar{y}^h)_{h \in \mathcal{T}_{p-1}}\right)|||_{\mathcal{L}(\beta, \gamma)} \leq c' |||(y^h - \bar{y}^h)_{h \in \mathcal{T}_{p-1}}|||_{\mathcal{L}(\beta, \gamma)} T^{\alpha - \beta}
\]
Hence, picking \( T \) small enough, we get that \( \theta := c' T^{\alpha - \beta} < 1 \). That is, for \( T \) small enough we have
\[
|||\mathcal{M}_T\left((y^h - \bar{y}^h)_{h \in \mathcal{T}_{p-1}}\right)|||_{\mathcal{L}(\beta, \gamma)} \leq \theta |||(y^h - \bar{y}^h)_{h \in \mathcal{T}_{p-1}}|||_{\mathcal{L}(\beta, \gamma)}
\]
for some \( \theta < 1 \) which establishes that \( \mathcal{M}_T \) is a contraction on \( \mathcal{D}_2^{(\beta, \gamma)}(\Delta^T_2([0, T]); \mathbb{R}^n) \).
This, together with the invariance of the ball for small enough \( T \) implies that \( \mathcal{M}_T \) has a unique fixed point in the ball \( \mathcal{B}_T \). This fixed point is the unique solution to the original equation in \( \mathcal{B}_T \).

**Step 3.** To finish the proof, we want to extend the solution to all of \( \Delta_2 \), which we do by constructing a solution on all intervals of length \( T \). That is, we construct a solution to (3.10) on \( \Delta^T_2((T, 2T)) \) using the terminal value of the solution created on \( \Delta^T_2([0, T]) \). Note that for any \( (t, \tau) \in \Delta^T_2((kT, (k+1)T)) \in \Delta_2 \) for some \( k \geq 1 \) we formally have that
\[
y_t^\tau = y_{kT}^{\tau - T} + \sum_{i=0}^d \int_{kT}^t k(\tau, r) f_i(y^\tau_r) dr,
\]
It follows, similarly as in the classical results on existence and uniqueness of SDEs, that there exists a solution on all subintervals of length $\bar{T}$, i.e., all intervals $[a, a + \bar{T}] \subset [0, T]$ for some $a \geq 0$. All these solutions are connected on the boundaries, and thus we use that a function which is Hölder on any subinterval of length $\bar{T}$ is also Hölder continuous on $[0, T]$ (see e.g. [PH14], exercise 4.24), which applies to the Hölder continuity in both variables. Notice that the time step $\bar{T}$ can be made constant thanks to the fact that exists a unique global solution to $\text{HSNO}^{\text{PI}}$ in the space $\mathcal{D}_2^{(\beta, \gamma)}(\mathbb{R}^e)$. We can conclude that there exists a unique global solution to (3.10) in the space $\mathcal{D}_2^{(\beta, \gamma)}(\Delta_2; \mathbb{R}^e)$ for $\beta < \alpha$. \hfill \Box

References


