DISCRETE EXTENSION OPERATORS FOR MIXED FINITE ELEMENT SPACES ON LOCALLY REFINED MESHES

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Abstract. The existence of uniformly bounded discrete extension operators is established for conforming Raviart-Thomas and Nédélec discretizations of $H(\text{div})$ and $H(\text{curl})$ on locally refined partitions of a polyhedral domain into tetrahedra.

1. Introduction

Many boundary value problems with non-homogeneous boundary data may be cast in the abstract variational form: find $u \in X$ such that $\gamma u = g \in M$ and

$$B(u, v) = F(v) \quad \forall v \in X_0$$

where $X$ is a Hilbert space over a domain $\Omega$, $M$ is a Hilbert space over the boundary $\Gamma$ of $\Omega$, and $\gamma : X \to M$ is a trace operator with $X_0 = \{ v \in X : \gamma v = 0 \}$. We assume that the bilinear and linear forms $B : X \times X \to \mathbb{R}$ and $F : X \to \mathbb{R}$ satisfy suitable conditions (e.g. inf-sup stability and continuity) for the problem to be well-posed; specific examples will be given later.

A Galerkin finite element approximation $u_h \approx u$ is obtained by selecting a finite dimensional subspace $X_h \subset X$, setting $M_h = \gamma X_h$, constructing a suitable approximation $g_h \approx g$ of the non-homogeneous boundary data, and seeking $u_h \in X_h$ such that $\gamma u_h = g_h \in M_h$ and

$$B(u_h, v_h) = F(v_h) \quad \forall v_h \in X_{h0} = \{ v_h \in X_h : \gamma v_h = 0 \}.$$  

The discrete problem (1.2) is well-posed provided that there exists a positive constant $\beta > 0$ such that

$$\sup_{v_h \in X_{h0}, \|v_h\|_X = 1} B(w_h, v_h) \geq \beta \|w_h\|_X \text{ for all } w_h \in X_{h0}.$$  

The issue of the accuracy of the resulting approximation is usually addressed by reference to the classical Céa type estimate

$$\|u - u_h\|_X \leq \left(1 + \frac{\kappa}{\beta}\right) \inf_{w_h \in X_h : \gamma w_h = g_h} \|u - w_h\|_X,$$

where $\kappa$ is the continuity constant of the bilinear form $B$. To prove this result one first proves an estimate for $u_h - w_h$ and then applies the triangle inequality. To do this, we note that $\gamma(u_h - w_h) = 0$, then apply (1.3), Galerkin orthogonality (e.g.
(1.1) and (1.2), and use continuity of $B$. As a side note, perhaps one can avoid using the triangle inequality by using the techniques in [23].

It is clear that the accuracy depends on both the choice of finite dimensional subspace $X_h \subset X$ and on the choice $g_h \approx g$ of the approximate Dirichlet boundary condition. Nevertheless, the bound (1.1) is somewhat unsatisfactory. In particular, whilst $X_h \subset X$ and $g_h \approx g$ can essentially be chosen independently of one another, the influence of each choice on the accuracy of the resulting finite element approximation is obscured through the requirement that the choice of comparator $w_h \in X_h$ is constrained to satisfy the boundary condition $\gamma w_h = g_h$.

Under what conditions is it possible to obtain an error estimate of the form

\[
\|u - u_h\|_X \leq C(\inf_{v_h \in X_h} \|u - v_h\|_X + \|g - g_h\|_M),
\]

in which the individual contributions to the error corresponding to the choice of $X_h \subset X$ and $g_h \approx g$ are isolated? Suppose that there exists a uniformly bounded discrete extension operator $L_h : M_h \rightarrow X_h$ such that

\[
(P1) \quad \gamma L_h \mu_h = \mu_h \quad \forall \mu_h \in M_h; \quad (P2) \quad \|L_h \mu_h\|_X \leq C_L \|\mu_h\|_M \quad \forall \mu_h \in M_h.
\]

Let $v_h \in X_h$ be arbitrary, and set $w_h = v_h - L_h(\gamma v_h - g_h) \in X_h$, so that $\gamma w_h = g_h$ on $\Gamma$ and $u_h - w_h \in X_{h0}$. With this choice, estimate (1.4) then gives

\[
\|u - u_h\|_X \leq (1 + \frac{\kappa}{2})\|u - v_h + L_h(\gamma v_h - g_h)\|_X.
\]

With the aid of the triangle inequality and (P2), the right hand side in the above estimate may be bounded by $\|u - v_h\|_X + C_L \|\gamma v_h - g_h\|_M$. The second term in this expression can be bounded by inserting $0 = \gamma u - g$, applying the triangle inequality and using the continuity of the trace operator $\gamma : X \rightarrow M$ to obtain $\|\gamma v_h - g_h\|_M \leq C\|v_h - u\|_X + \|g - g_h\|_M$. Combining the above estimates, we conclude that (1.5) holds whenever there exists a discrete extension operator satisfying (P1)-(P2). Interestingly, the existence of an operator satisfying (P1)-(P2) is also necessary for a bound of the form (1.5) to hold [13,20].

The existence of uniformly bounded discrete extension operators satisfying (P1)-(P2) is important in many areas of numerical analysis, including the construction of domain decomposition preconditioners [24]. The main purpose of the current work is to establish the existence of discrete extension operators satisfying (P1)-(P2) in the case where the discrete spaces are taken to be conforming discretizations of $H(\text{div})$ and $H(\text{curl})$, i.e. Raviart-Thomas and Nédélec spaces, on general shape regular mesh partitioning of a polyhedral domain into tetrahedra.

Various results concerning stable extension operators are interspersed in the literature. There are a number of results available in the literature concerning discrete extensions from the boundary to the interior on a single isolated element [12], but the fact that the norms on the trace spaces are not additive means that one cannot prove the results for collections of elements by simply summing contributions from individual elements. The case of Raviart-Thomas elements on a two-dimensional domain appears in [4] applied to the analysis of weakly imposed essential boundary conditions for the mixed Laplacian for the case of quasi-uniform triangulations, and was subsequently extended [14] to cover meshes that are quasi-uniform in a neighborhood of the boundary. Subsequently, the case of general non-quasi-uniform meshes was covered in [17], although, unfortunately, the arguments used seem to be limited to the two-dimensional setting. Stable discrete extensions for $H(\text{curl}, \Omega)$
conforming spaces have also appeared in the literature and have important applications; see \[1,15,16\]. Again, the results in these articles assume some degree of quasi-uniformity.

The approach employed in the present work for the treatment of Raviart-Thomas elements is similar to the idea used in \[4, Lemma 3.2\] and \[14, Lemma 5.1\] without, however, requiring quasi-uniformity of the mesh. The key to relaxing the conditions on the mesh is to develop local regularity estimates along with discrete norm equivalences valid on general shape regular meshes \[2\] and to show that the operator defined in \[14\] is, in fact, uniformly bounded on general shape regular meshes.

The proof of a bounded discrete extension operator for Néédélec spaces is similar to a proof found in \[15\]. The idea is to first split the discrete trace using a discrete Hodge decomposition and to then use our extension result for Raviart-Thomas elements to handle one component of the splitting, with the remaining component treated using an idea adapted from \[17\]. The resulting extension yields a divergence-free field which therefore belongs to Brezzi-Douglas-Marini space. Consequently, our results for the Raviart-Thomas case (i.e. Néédélec spaces in the three-dimensional case \[18\]) extend to the three-dimensional counterpart of the Brezzi-Douglas-Marini finite element \[9,19\].

The plan of the paper is as follows. The main results are stated in Section 2. Proofs are given in Sections 3 for the Raviart-Thomas elements, and in Section 4 for the Néédélec elements. The local regularity estimates needed in Section 3 are given in the Appendix. Basic results on the spaces \(H^1(\Omega)\), \(H(\text{div},\Omega)\), and \(H(\text{curl},\Omega)\) will be assumed throughout. The symbol \(\lesssim\) will be used as follows: for two quantities \(a_h\) and \(b_h\) depending on the triangulations (see below), we write \(a_h \lesssim b_h\) whenever there exists \(C > 0\) independent of \(h\) such that \(a_h \leq C b_h\). The quantity \(C\) will be allowed to depend on: the polynomial degree, the shape-regularity of the triangulation, and the domain.

2. Main results

Let \(\Omega \subset \mathbb{R}^3\) be a connected polyhedral Lipschitz domain. The unit outward pointing normal vector field on \(\Gamma := \partial \Omega\) will be denoted by \(\mathbf{n}\). Now let \(\mathcal{T}_h\) be a shape regular simplicial triangulation of \(\Omega\) which, however, need not be quasi-uniform. For each \(K \in \mathcal{T}_h\) we let \(h_K\) denote the diameter of \(K\). We then consider the spaces of Raviart-Thomas and Néédélec finite elements:

\[
\begin{align*}
V_h & := \{ q \in H(\text{div},\Omega) : q|_K \in \mathcal{P}^k(K)^3 + \mathcal{P}^k(K) \mathbf{x}, \text{ for all } K \in \mathcal{T}_h \}, \\
N_h & := \{ q \in H(\text{curl},\Omega) : q|_K \in \mathcal{P}^k(K)^3 + \mathcal{P}^k(K)^3 \times \mathbf{x}, \text{ for all } K \in \mathcal{T}_h \},
\end{align*}
\]

where \(\mathcal{P}_k(S)\) is the space of polynomials of degree \(k\) or less defined on \(S\). On the boundary \(\Gamma\), we consider the induced triangulation,

\[\Gamma_h = \{ \partial \Omega \cap \partial K : \text{ for all } K \in \mathcal{T}_h \},\]

and two spaces:

\[
\begin{align*}
M_h & := \{ q \cdot \mathbf{n} : q \in V_h \} = \{ v : v|_F \in \mathcal{P}^k(F) \text{ for all } F \in \Gamma_h \}, \\
R_h & := \{ q \times \mathbf{n} : q \in N_h \} = \{ r \in H(\text{div},\Gamma) : r|_F \in \mathcal{P}^k(F)^2 + \mathcal{P}^k(F) \mathbf{x}_t \text{ for all } F \in \Gamma_h \}.
\end{align*}
\]
defined as follows: for non-negative integer $k$ and $0 < s < 1$, we define
\[
\|v\|_{H^{k+s}(S)}^2 = \|v\|_{H^k(S)}^2 + |v|_{H^{k+s}(S)}^2,
\]
where
\[
|v|_{H^{k+s}(S)}^2 = \sum_{|\alpha|=k} \int_S \int_S \frac{|\partial^\alpha v(x) - \partial^\alpha v(y)|^2}{|x-y|^{d+2s}} dxdy
\]
is the Slobodetskij seminorm and $\| \cdot \|_{H^k(S)}$ is the usual Sobolev norm. For negative $s$, $H^{-s}(S)$ is the dual space of $H_0^s(S)$, the closure in $H^s(S)$ of the set of smooth compactly supported functions. In particular, in the case of the closed surface $\Gamma$, we can write for functions $v \in L^2(\Gamma)$:
\[
\|v\|_{H^{-1/2}(\Gamma)} = \sup_{w \in C^\infty(\Gamma), \|w\|_{H^{1/2}(\Gamma)} = 1} \int_\Gamma vw.
\]
As noted before, the operator $V_h \ni v \mapsto v \cdot n \in M_h$ is surjective. The next result shows that there is a right-inverse of this operator that is bounded as an operator $H^{-1/2}(\Gamma) \to H(\text{div}; \Omega)$, uniformly in the mesh size. Using the result [17, Theorem 5.1] it is enough to establish the uniform extension for data in $M_0^h$.

**Theorem 2.1.** There exists a constant $C$ depending only on the shape regularity of $T_h$ and on $\Omega$ such that for any $g_h \in M_h^0$ there exists $\sigma_h \in V_h$ with the following properties:

(a) $\sigma_h \cdot n = g_h$ on $\Gamma$,
(b) $\|\sigma_h\|_{H(\text{div}; \Omega)} \lesssim \|g_h\|_{H^{-1/2}(\partial \Omega)}$,
(c) $\text{div} \sigma_h = 0$ in $\Omega$.

The second result concerns the Nédelec space, asserting the existence of a uniformly bounded right-inverse of the operator $N_h \ni w_h \mapsto w_h \times n \in R_h$.

In order to state the result we need to define the trace space of the curl operator,
\[
H_{||}^{-1/2}(\text{div}\Gamma; \Gamma) := \{ r \in H_{||}^{-1/2}(\Gamma) : \text{div} r \in H^{-1/2}(\Gamma) \},
\]
with norm
\[
\|r\|_{H_{||}^{-1/2}(\text{div}\Gamma; \Gamma)}^2 = \|r\|_{H_{||}^{-1/2}(\Gamma)}^2 + \|\text{div} r\|_{H^{-1/2}(\Gamma)}^2.
\]
The space $H_{||}^{-1/2}(\Gamma)$ along with the norm are defined in [6]; see also [7,8].

In [6] the following continuity result was proved.

**Proposition 2.2.** For $w \in H(\text{curl}; \Omega)$, $w \times n \in H_{||}^{-1/2}(\text{div}\Gamma; \Gamma)$ with the bound
\[
(2.1) \quad \|w \times n\|_{H_{||}^{-1/2}(\text{div}\Gamma; \Gamma)} \lesssim \|w\|_{H(\text{curl}; \Omega)}.
\]

**Theorem 2.3.** There exists a constant $C$ depending only on the shape regularity of $T_h$ and on $\Omega$ such that for any $r_h \in R_h$ there exists $w_h \in N_h$ with the following properties:

(a) $w_h \times n = r_h$ on $\Gamma$,
(b) $\|w_h\|_{H(\text{curl}; \Omega)} \lesssim \|r_h\|_{H_{||}^{-1/2}(\text{div}\Gamma; \Gamma)}$.
We first recall some properties of the Raviart-Thomas projection. Let \( v \in H^{1/2+s}(\Omega) \) for some \( s > 0 \). Then we define \( \Pi v \in V_h \) satisfying

\[
\int_F (\Pi v \cdot n)w = \int_F (v \cdot n)w \quad \forall w \in \mathcal{P}^k(F) \quad \forall F \in \mathcal{E}_h,
\]

\[
\int_K \Pi v \cdot w = \int_K v \cdot w \quad \forall w \in [\mathcal{P}^k-1(K)]^3 \quad \forall K \in \mathcal{T}_h
\]

(see [5, Example 2.5.3]). Here \( \mathcal{E}_h \) is the set of all faces of the triangulation. The following classical result can be found in [5, Propositions 2.5.1, 2.5.2].

**Proposition 3.1.** For every \( v \in (H^{1/2+s}(\Omega))^3 \) one has

(a) \( \text{div} \, \Pi v = P \text{div} \, v \),

(b) \( \| \Pi v - v \|_{L^2(K)} \lesssim h^{1/2+s}_K \| v \|_{H^{1/2+s}(K)} \) for all \( K \in \mathcal{T}_h \),

where \( P \) is the \( L^2(\Omega) \)-orthogonal projection onto the space of piecewise \( \mathcal{P}^k(K) \) functions.

The following inverse inequality will play a key role in our analysis.

**Lemma 3.2.** For any \( g \in M_h \) we have

\[
\sum_{F \in \Gamma_h} h_F^2 \| g_h \|_{L^2(F)}^2 \lesssim \| g_h \|_{H^{-1/2}(\Gamma)}^2.
\]

**Proof.** This result is a consequence of basic estimates given in [2]. Let \( \{ \varphi_{i,F} : i = 1, \ldots, \dim \mathcal{P}^k(F) \} \) be a basis for \( \mathcal{P}^k(F) \) built by pushing forward the Lagrange basis on the reference element. Then we decompose \( g_h = \sum_F \sum_i g_{i,F} \varphi_{i,F} \) and estimate

\[
\sum_{F \in \Gamma_h} h_F^2 \| g_h \|_{L^2(F)}^2 \lesssim \sum_F \sum_i h_F^3 |g_{i,F}|^2 \| \varphi_{i,F} \|_{L^2(F)}^2
\]

\[
\lesssim \sum_F \sum_i h_F^3 |g_{i,F}|^2 
\]

\[
\lesssim \sum_F \sum_i \| g_{i,F} \varphi_{i,F} \|_{H^{-1/2}(\Gamma)}^2 
\]

\[
\lesssim \| g_h \|_{H^{-1/2}(\Gamma)}^2 
\]

(by [2, Theorem 4.8]),

which finishes the proof. \( \square \)

We also need elliptic regularity results; see for example [11] for the case \( g = 0 \). Consider the Poisson problem with Neumann boundary conditions

\[
(3.1a) \quad -\triangle u = f \quad \text{on } \Omega,
\]

\[
(3.1b) \quad \nabla u \cdot n = g \quad \text{on } \Gamma,
\]

under the assumption that \( \int_\Gamma g + \int_\Omega f = 0 \) and \( \int_\Omega u = 0 \). Then, there exist \( C > 0 \) and \( s \in (0, 1/2) \) such that

\[
\| u \|_{H^{3/2+s}(\Omega)} \leq C \left( \| f \|_{H^{-1/2+s}(\Omega)} + \| g \|_{H^{-1/2}(\Gamma)} \right).
\]

We can localize this regularity result to obtain:
Theorem 3.3. Suppose that \( f \equiv 0 \) in (3.1) and let \( \sigma = \nabla u \). Then for each \( K \in \mathcal{T}_h \) we have
\[
\|\sigma\|_{H^{1/2+s}(K)} \leq C(h^{-1/2-s}_K \|\sigma\|_{L^2(D_K)} + \|g\|_{H^s(\partial D_K \cap \Gamma)} + h^{-s}_K \|g\|_{L^2(\partial D_K \cap \Gamma)}),
\]
where
\[
D_K := \bigcup \{K' \in \mathcal{T}_h : \overline{K} \cap \overline{K'} \neq \emptyset\}
\]
is the collection of tetrahedra sharing one or more vertices with \( K \).

Remark. It would be very interesting to investigate if a similar result can be proved in the case the extension is needed for part of the boundary \( \partial \Omega \). Extension results for part of the boundary are important for transmission problems such as Stokes-Darcy flows.

Proof of Theorem 2.1 Let \( u \) satisfy
\[
-\Delta u = 0 \quad \text{on} \ \Omega,
\]
\[
\nabla u \cdot n = g_h \quad \text{on} \ \Gamma,
\]
and set \( \sigma = \nabla u \in (H^{1/2+s}(\Omega))^3 \) (see (3.2)). Note that \( \text{div} \ \sigma = 0 \). We define \( \sigma_h = \Pi \sigma \) and we note that Theorem 2.1(a) holds and that by Proposition 3.1(a), \( \text{div} \ \sigma_h = 0 \). Therefore, using elliptic regularity, Proposition 3.1(b) and Lemma 3.2,
\[
\|\sigma_h\|_{H^1(\Omega)} = \|\sigma_h\|_{L^2(\Omega)} \leq \|\sigma\|_{L^2(\Omega)} + \|\sigma_h\|_{L^2(\Omega)}
\]
\[
\lesssim \|g_h\|_{H^{-1/2}(\Gamma)} + \|\sigma_h\|_{L^2(\Omega)} \lesssim \|g_h\|_{H^{-1/2}(\Gamma)} + \left( \sum_{K \in \mathcal{T}_h} h^{2(1/2+s)}_K \|\sigma\|^2_{H^{1/2+s}(K)} \right)^{1/2}
\]
\[
+ \left( \sum_{K \in \mathcal{T}_h} \|\sigma_h\|^2_{L^2(D_K)} + h^{2(1/2+s)}_K \|g_h\|^2_{H^s(\partial D_K \cap \Gamma)} + h_K \|g_h\|^2_{L^2(\partial D_K \cap \Gamma)} \right)^{1/2}.
\]

The shape regularity of the elements means that
\[
\sum_{K \in \mathcal{T}_h} \|\sigma\|^2_{L^2(D_K)} \lesssim \|\sigma\|^2_{L^2(\Omega)}.
\]

Also, if we let \( D_F \) be the macro-element surrounding \( F \) (triangles sharing a vertex with \( F \)), we have that
\[
\sum_{K \in \mathcal{T}_h} h^{2(1/2+s)}_K \|g_h\|^2_{H^s(\partial D_K \cap \Gamma)} \lesssim \sum_{F \in \mathcal{T}_h} h^{2(1/2+s)}_F \|g_h\|^2_{H^s(D_F)}
\]
\[
\lesssim \sum_{F \in \mathcal{T}_h} h_F \|g_h\|^2_{L^2(D_F)} \lesssim \sum_{F \in \mathcal{T}_h} h_F \|g_h\|^2_{L^2(F)},
\]
where we have used a standard local inverse estimate for piecewise polynomial functions. Applying Lemma 3.2 completes the proof.

As an application we can get an error estimate for the Laplacian in mixed form with Neumann boundary conditions. In this case \( X = H(\text{div}, \Omega) \times L^2(\Omega) \), and the
trace space is $M = H^{-1/2}(\partial\Omega)$ with trace operator $\gamma(\sigma, u) = \sigma \cdot n$. The bilinear form $B$ and the linear form $F$ are given by

$$B((\sigma, u), (\eta, w)) := \int_{\Omega} (\sigma \cdot \eta - u \text{ div } \eta + w \text{ div } \sigma),$$

$$F((\eta, w)) := \int_{\Omega} fw,$$

for a given $f \in L^2$. Of course, the finite element space will be $X_h = V_h \times U_h$ where $U_h = \{w : \Omega \to \mathbb{R} : w|_K \in P^k(K) \ \forall K \in T_h\}$.

In view of Theorem 2.1 and the introductory discussion, we have the following error estimates for Raviart-Thomas elements.

**Corollary 3.4.** Let $X = H(\text{div}, \Omega) \times L^2(\Omega)$, $M = H^{-1/2}(\partial\Omega)$ and $X_h = V_h \times U_h$. Let $(\sigma, u)$ satisfy (1.1) and $(\sigma_h, u_h)$ satisfy (1.2). Then the following holds:

$$\|\sigma - \sigma_h\|_{H(\text{div},\Omega)} + \|u - u_h\|_{L^2(\Omega)} \lesssim \inf_{v \in V_h} \|\sigma - v\|_{H(\text{div},\Omega)} + \inf_{w \in U_h} \|u - w\|_{L^2(\Omega)} + \|g - g_h\|_{H^{-1/2}(\Gamma)}.$$

Finally, we note that other applications of the existence of an extension operator like $L_h$ are given in the analysis of a variety of discretization methods for the Stokes-Darcy problem [11][17].

4. **Discrete Extension Operators for Nédélec Finite Element Spaces**

The proof of Theorem 2.3 relies on a Helmholtz-Hodge type decomposition of $R_h$, two liftings (one for Lagrange finite elements and the one provided by Theorem 2.1), and local estimates in the space of Lagrange finite elements on the boundary

$$P_h := \{\phi_h \in C(\Gamma) : \phi_h|_F \in P_{k+1}(F) \text{ for all } F \in T_h\}.$$

We begin with some technical results:

**Lemma 4.1.** If $r_h \in R_h$ satisfies $\text{div } r_h = 0$, then $r_h = \text{curl}_\Gamma \phi_h$ with $\phi_h \in P_h$.

**Proof.** By definition of $R_h$, there exists $w_h \in N_h$ such that $w_h \times n = r_h$. Note now that

$$q_h := \nabla \times w_h \in V_h, \quad q_h \cdot n = \text{div}_\Gamma (w_h \times n) = 0.$$

Therefore, by the exactness of the discrete de Rham complex with essential boundary conditions (see for example [3]), there exists $w_h^0 \in N_h$ such that $\nabla \times w_h^0 = q_h$ and $w_h^0 \times n = 0$. We then consider the difference $w_h - w_h^0$ and note, again, by the exactness of the discrete de Rham complex there exists $u_h$ in the finite element space

$$W_h := \{u_h \in C(\Omega) : u_h|_K \in P_{k+1}(K) \text{ for all } K \in T_h\},$$

satisfying $\nabla u_h = w_h - w_h^0$. Take $\phi_h = u_h|_\Gamma$. The result follows since $w_h \times n = \nabla u_h \times n = \text{curl}_\Gamma \phi_h$.

We will also need the following result found for example in [5].

**Lemma 4.2.** For all $\phi \in H^{1/2}(\Gamma)$ we have

$$\|\phi\|_{H^{1/2}(\Gamma)/\mathbb{R}} \lesssim \|\text{curl}_\Gamma \phi\|_{H^{-1/2}(\Gamma)}.$$
Lemma 4.3. For all $v_h \in V_h$ with $\text{div} v_h = 0$, there exists $w_h \in N_h$ such that $\nabla \times w_h = v_h$ and $\|w_h\|_{L^2(\Omega)} \lesssim \|v_h\|_{L^2(\Omega)}$.

Proof. By uniformly bounded projections $\Pi_h : H(\text{curl}, \Omega) \rightarrow N_h$ and $Q_h : H(\text{div}, \Omega) \rightarrow V_h$ exist such that $\nabla \times \Pi_h w = Q_h(\nabla \times w)$ for all $w \in H(\text{curl}, \Omega)$. On the other hand the curl operator is surjective from $H(\text{curl}, \Omega)$ to $\{v \in H(\text{div}, \Omega) : \text{div} v = 0\}$ and therefore has a bounded right-inverse. We then apply this right-inverse to $v_h$ to obtain $w \in H(\text{curl}, \Omega)$ and define $w_h = \Pi_h w$. Then $\nabla \times w_h = Q_h(\nabla \times w) = Q_h v_h = v_h$ and the result is proved.

Proof of Theorem 2.3 Let $r_h \in R_h$. Then $\text{div}_\Gamma r_h \in M^0_h$, and by Theorem 2.1 we can find $v_h \in V_h$ such that

$$\text{div} v_h = 0, \quad v_h \cdot n = \text{div}_\Gamma r_h,$$

and

$$\|v_h\|_{H(\text{div}, \Omega)} \lesssim \|\text{div} r_h\|_{H^{-1/2}(\Gamma)}.$$

We then use Lemma 4.3 to obtain $w_h \in N_h$ such that $\nabla \times w_h = v_h$ and

$$\|w_h\|_{H(\text{curl}, \Omega)} \lesssim \|v_h\|_{H(\text{div}, \Omega)} \lesssim \|\text{div} r_h\|_{H^{-1/2}(\Gamma)}.$$

Consider now the function $m_h := r_h - w_h \times n \in R_h$ and note that

$$\|m_h\|_{H^{-1/2}(\Gamma)} \lesssim \|r_h\|_{H^{-1/2}(\Gamma)} + \|\text{div}_\Gamma r_h\|_{H^{-1/2}(\Gamma)}$$

by (4.2) and the continuity of the tangential trace operator from $H(\text{curl}, \Omega)$ to $H^{-1/2}(\text{div}_\Gamma; \Gamma)$. Additionally,

$$\text{div}_\Gamma m_h = \text{div}_\Gamma r_h - (\nabla \times w_h) \cdot n = 0,$$

by construction of $w_h$. We then apply Lemma 4.1 to find $\phi_h \in P_h$ such that $r_h - w_h \times n = \text{curl}_\Gamma \phi_h$ and use Lemma 4.2 to bound

$$\|\phi_h\|_{H^{1/2}(\Gamma)/R} \lesssim \|r_h - w_h \times n\|_{H^{-1/2}(\Gamma)} \lesssim \|r_h\|_{H^{-1/2}(\Gamma)} + \|\text{div}_\Gamma r_h\|_{H^{-1/2}(\Gamma)},$$

where we used (2.1) and (4.2).

We then take $u_h$ in the finite element space $W_h$ (see (4.1)) such that $u_h|_{\Gamma} = \phi_h$ and

$$\|u_h\|_{H^1(\Omega)/R} \lesssim \|\phi_h\|_{H^{1/2}(\Gamma)/R}.$$

This can be accomplished by first taking $u \in H^1(\Omega)$ whose trace is $\phi_h$ and satisfying $\|u\|_{H^1(\Omega)/R} \lesssim \|\phi_h\|_{H^{1/2}(\Gamma)/R}$ and then applying the Scott-Zhang interpolation operator $[22]$ to $u$. The desired lifting of $r_h$ is the function $w_h + \nabla u_h \in N_h$. The bound

$$\|w_h + \nabla u_h\|_{H(\text{curl}, \Omega)} \leq \|w_h\|_{H(\text{curl}, \Omega)} + \|\nabla u_h\|_{L^2(\Omega)} \lesssim \|r_h\|_{H^{1/2}(\Gamma)} + \|\text{div}_\Gamma r_h\|_{H^{-1/2}(\Gamma)}$$

is a direct consequence of (4.2), (4.3), and (4.4). The fact that it is a lifting follows from

$$(w_h + \nabla u_h) \times n = w_h \times n + \text{curl}_\Gamma \phi_h = w_h \times n + m_h = r_h.$$
As an application to Theorem 2.3 we consider problem (1.1) with
\[ X = H(\text{curl}; \Omega), \]
\[ M = H^{1/2}(\text{div}; \partial \Omega) := \{ \mu \in H^{1/2}(\partial \Omega) : \text{div} \mu \in H^{1/2}(\partial \Omega) \}. \]
The finite element space comprises the Nédélec elements \( X_h = N_h \). The bilinear form \( B \) and linear form \( F \) are as follows:
\[ B(u, v) = \int_{\Omega} (\nabla \times u) \cdot (\nabla \times v) + u \cdot v, \]
\[ F(v) = \int_{\Omega} f \cdot v. \]

Theorem 2.3 and the introductory discussion now give the following error estimates for Nédélec elements.

**Corollary 4.4.** Let \( X = H(\text{curl}; \Omega) \), \( M = H^{1/2}(\text{div}; \partial \Omega) \) and \( X_h = N_h \). Let \( u \) satisfy (1.1) and \( u_h \) satisfy (1.2). Then the following holds:
\[ \| u - u_h \|_{H(\text{curl}; \Omega)} \lesssim \inf_{v \in N_h} \| u - v \|_{H(\text{curl}; \Omega)} + \| g - g_h \|_{H^{1/2}(\text{div}; \Gamma)}, \]

**Appendix A. Proof of Theorem 3.3**

For each \( K \in \mathcal{T}_h \) we can find a cut-off function \( \omega = \omega_K \in C^\infty(D_K) \) with the following properties:

(A.1a) \( \omega \equiv 1 \) in \( K \),
(A.1b) \( \omega \equiv 0 \) in \( \Omega \setminus D_K \),
(A.1c) \( \| D^s \omega \|_{L^\infty(D_K)} \lesssim h_K^{-s} \) for \( s = 0, 1, 2 \).

Note that
\[ \| u \|_{H^{3/2+s}(K)} \lesssim \| \nabla u \|_{H^{3/2+s}(\Omega)} \leq C(\| -\Delta (\omega u) \|_{H^{-1/2+s}(\Omega)} + \| \nabla (\omega u) \cdot n \|_{H^s(\Gamma)}), \]
by (3.2). Here the constant depends only on \( \Omega \).

Let us first deal with elements \( K \) such that \( D_K \) does not contain a face in \( \partial \Omega \). In this case \( \nabla (\omega u) \cdot n \equiv 0 \) on \( \partial \Omega \). To bound the first term we let \( v \in H^{1/2-s}(\Omega) \) and define \( m(v) = \frac{1}{|D_K|} \int_{D_K} v \). Then, we have
\[ -\int_{\Omega} \Delta (\omega u) v = -\int_{\Omega} \Delta (\omega u) (v - m(v)) - \int_{\Omega} \Delta (\omega u) m(v) \]
\[ = -\int_{\Omega} (2 \nabla \omega \cdot \nabla u + u \Delta \omega) (v - m(v)), \]
where we used that \( \Delta u = 0 \) and that \( \nabla (\omega u) \cdot n \equiv 0 \) on \( \partial \Omega \). Therefore
\[ -\int_{\Omega} \Delta (\omega u) v \leq (\| \nabla \omega \cdot \nabla u \|_{L^2(D_K)} + \| u \Delta \omega \|_{L^2(D_K)}) \| v - m(v) \|_{L^2(D_K)} \]
\[ \lesssim (h_T^{-1/2-s} \| \nabla u \|_{L^2(D_K)} + h_K^{-3/2-s} \| u \|_{L^2(D_K)}) \| v \|_{H^{1/2-s}(D_K)}, \]
where we have used (A.1c), the Poincaré inequality and an interpolation argument. Taking the supremum over \( v \) we have
\[ \| -\Delta (\omega u) \|_{H^{-1/2+s}(\Omega)} \leq (h_K^{-1/2-s} \| \nabla u \|_{L^2(D_K)} + h_K^{-3/2-s} \| u \|_{L^2(D_K)}). \]
Hence, in the case $D_K$ does not contain a face in $\partial\Omega$ we have
\[
\|u\|_{H^{3/2+s}(K)} \lesssim (h_K^{-1/2-s}\|\nabla u\|_{L^2(D_K)} + h_K^{-3/2-s}\|u\|_{L^2(D_K)}).
\]
If we replace $u$ with $m(u)$ and note that
\[
\|u - m(u)\|_{L^2(D_K)} \lesssim h_K\|\nabla u\|_{L^2(D_K)},
\]
we get
\[
\|\nabla u\|_{H^{1/2+s}(K)} \lesssim h_K^{-1/2-s}\|\nabla u\|_{L^2(D_K)}.
\]

Next we consider the case when $\partial D_K$ contains one or more faces on $\Gamma$. To bound the first term in the right of (A.2) we get
\[
\int_\Omega \Delta(\omega u)v \leq (2\|\nabla \omega \cdot \nabla u\|_{L^2(D_K)} + \|u\Delta\omega\|_{L^2(D_T)})\|v\|_{L^2(D_K)}
\leq (h_K^{-1/2-s}\|\nabla u\|_{L^2(D_K)} + h_K^{-3/2-s}\|u\|_{L^2(D_K)})h_K^{1/2-s}\|v\|_{H^{1/2-s}(D_K)},
\]
where we have used (A.1c) and the fact that $v$ vanishes on at least one face of $\partial D_K$, which allows us to use an inequality in the form
\[
(A.3) \quad \|v\|_{L^2(D_K)} \lesssim h_K^{1/2-s}\|v\|_{H^{1/2-s}(D_K)}.
\]

Therefore, as above we have that
\[
\| - \Delta(\omega u)\|_{H^{-1/2+s}(\Omega)} \lesssim h_K^{-1/2-s}\|\nabla u\|_{L^2(D_K)} + h_K^{-3/2-s}\|u\|_{L^2(D_K)}.
\]

To bound the second term on the right of (A.2) we first use the product rule and get
\[
\|\nabla(\omega u) \cdot n\|_{H^s(\partial\Omega)} \lesssim \|u\nabla\cdot n\|_{H^s(\partial\Omega)} + \|\omega g\|_{H^s(\Gamma)}
\lesssim h_K^{-1/2-s}\|u\nabla\|_{L^2(D_T)} + h_K^{1/2-s}\|\nabla(u\nabla)\|_{L^2(D_T)} + \|\omega g\|_{H^s(\Gamma)}
\lesssim h_K^{-3/2-s}\|u\|_{L^2(D_T)} + h_K^{-1/2-s}\|\nabla u\|_{L^2(D_T)} + \|\omega g\|_{H^s(\Gamma)},
\]
after using a localized version of the trace theorem and (A.1c). By a simple interpolation argument and (A.1c), we have
\[
\|\omega g\|_{H^s(\Gamma)} \lesssim \|g\|_{H^s(\partial D_K \cap \Gamma)} + h_K^{-s}\|g\|_{L^2(\partial D_K \cap \Gamma)}.
\]

Combining the above inequalities we have
\[
\|u\|_{H^{3/2+s}(K)} \lesssim (h_K^{-1/2-s}\|\nabla u\|_{L^2(D_K)} + h_K^{-3/2-s}\|u\|_{L^2(D_K)})
+ (\|g\|_{H^s(\partial D_K \cap \Gamma)} + h_K^{-s}\|g\|_{L^2(\partial D_K \cap \Gamma)}).
\]

If we apply the above argument to $u - m(u)$, we obtain our result.

Acknowledgements

The authors would like to thank Norbert Heuer for several useful discussions. Also, they thank Ralf Hiptmair for bringing the relevant papers [1,15,16] to their attention.
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